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MTIAC

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LASER CUTTING

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IIT Research Institute

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This state-of-the-art review covers laser cutting processes, laser source configurations, and multiaxis manipulators for directing the laser beam. Cutting process data are documented for carbon steel, stainless steel, aluminum alloys, high-temperature alloys, titanium alloys, plastics, and composites. The plastics include acrylics and polycarbonates, and the composites were Kevlar, glass/epoxy, graphite/epoxy, and boron/aluminum. Where available, data relating to cutting speed, roughness of the cut face, kerf width, relative freedom from dross or burrs, and maximum cuttable thickness are listed for each material. Laser source configurations pertain to both CO_2 and Nd:YAG technologies. Slow-axial-flow, fast-axial-flow, and fast-transverse-flow configurations are described for the CO_2 technology, including maximum available power (CW), pulsing modes, and discharge stabilization techniques for these CO_2 configurations. Single, optically modified, and multiple cavity configurations are described for the Nd:YAG technology; maximum power, pulse configuration, and types of power supply are indicated. Subsonic supersonic assist gas technology is described, and the noncircular or

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fluted gas jet is noted. Two levels of manipulator technology are covered. The lower level is nonprogrammable with respect to cut path; the higher level permits complex path programming in two dimensions (flat stock) or three dimensions using two, three, five, or six axes. Laser robotic manipulators are discussed in terms of commercial work-handling lasers and special gantry manipulators designed for use with lasers, including hybrids and open-sided variations of the gantry laser.

PREFACE

This state-of-the-art review was prepared by the Manufacturing Technology Information Analysis Center (MTIAC) under Contract DLA900-84-C-1508 for the Department of Defense.

The review covers the use of commercially available industrial laser systems for the cutting of metallic and nonmetallic materials in manufacturing applications. The content has been selected to present a picture of the following:

- Level of process performance that can be expected.
- State-of-the-art equipment that is available in terms of:
  - (a) the laser that produced the above performance.
  - (b) the manipulators that bring the laser performance to various types of workpieces.

Process performance has been documented for carbon steel, stainless steel, aluminum, high-temperature alloys, and several nonmetallic materials. A section has been devoted to the rapidly emerging field of composites. For each material available, data regarding cutting speed, kerf width, edge quality, and maximum cuttable thickness have been documented. Emphasis has been placed on advantages and disadvantages of pulsed power processes.

The information on lasers covers carbon dioxide (CO_2) technology, which has dominated cutting in the past. However, the growing importance of fiber optic beam manipulating has resulted in increased emphasis on neodymium: yttrium-aluminum-garnet (Nd:YAG) lasers because their beams can be directed through available quartz fibers. Additionally, new Nd:YAG power levels that challenge multikilowatt CO_2 lasers are discussed. Because of their potential for cutting plastics without recourse to burning, the industrial status of excimer lasers have been reviewed. A section has been devoted to optional Nd:YAG and CO_2 laser configurations that permit a new, wide latitude in balancing power against beam quality. This discussion covers slow-axial-flow, fast-axial-flow, and fast-transverse-flow CO_2 laser configurations as well as

single and multiple cavity, optically modified, and unmodified Nd:YAG lasers. The status of slab lasers is considered. The availability of four pulsed power modes for CO_2 lasers is noted, and the application of each is discussed. New developments are presented regarding the use of supersonic assist gas jets to enhance the basic laser cutting capability and on the implications to users in terms of electing advanced gas nozzle designs and, possibly, reducing standoff distance.

The rapid advance of manipulator technology has necessitated devoting one section of this state-of-the-art review to a classification of existing and emerging configurations. Thus nonprogrammable path and programmable path manipulators are described. In the latter category, systems where the work moves while the beam is stationary and the newer "flying optic" systems where the reverse is true are discussed and illustrated. The status of attempts to link lasers to commercial work-handling robots is covered. Other system approaches discussed include the five- or six-axis moving-optic, gantry robot. These robot-manipulators are specially designed for three-dimensional application, and a "hybrid" variant that increases throughput at the expense of floor space is also reviewed. Tabulations of advantages/disadvantages have been included to assist the reader in relating these several configurations to candidate workpieces.

The content of this review has been derived from over 30 references. However, the subjects of lasers, laser processes, and manipulator systems is constantly evolving. Thus, after information from the references had been assembled, it was sent to experts with a strong day-to-day involvement in the specification and implementation of cutting systems. The comments of the following experts greatly assisted in updating published information to produce this state-of-the-art assessment:

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SUMMARY

This review considers the three aspects of laser cutting that define the state-of-the-art (SOA):

- Process performance
- Laser beam sources
- Laser beam/work manipulators.

Emphasis has been placed on equipment and processes that are commercially available and relate to the material working industry.

Process Performance. The first part of the review describes the qualitative and quantitative performance that make up the process state of the art. The relationship between quality and quantity reveals that overly slow or overly fast cutting speeds result in poor quality. The range of acceptable quality is greatest for thin sheet and narrows as the workpiece thickness approaches that of light plate. The perpendicularity and flatness of the face of the cut and the undesirable presence of dross or metal burrs on the underside of the cut are the quality elements that are affected by the foregoing relationships.

The review also documents an emerging recognition of the relationship between cut face roughness and the delivery of beam power in the form of a series of pulses rather than in the continuous (CW) mode. The study recognizes a further relationship between the velocity of the cutting gas and process speed. Finally, the dramatic effect on cut face separation (often called "kerf width") and parallelism caused by beam polarization is noted. Equipment to control these conditions is described in the Section 4.

The remainder of the section on process performance documents quantitative performance data. Data for carbon dioxide (CO_2), both CW and pulsed power, and neodymium:yttrium-aluminum-garnet (Nd:YAG) technologies are included. Nd:YAG always operates in the pulsed mode at the power levels of interest in this study. Materials have been selected for their interest in the defense manufacturing community as well as general industry and include:

- Carbon steel
- Stainless steel and high-temperature-nickel base alloys
- Aluminum
- Titanium
- Nonmetallics

Carbon steel data reveal that 1 kW cutting speeds of 340 ipm can be expected on 0.04 in. material with a resulting 800 μin. cut face roughness at a kerf width of about 0.004 in. and a heat-affected zone depth behind the cut face of 0.003 in. contrasted with depths of 0.030 in. reported in 1975. Carbon steel is usually cut using CW power. Data for pulsed power suggest only a slight reduction in speed at a given power level while surface roughness is reduced to 120 μin. Qualities such as surface roughness and kerf width are important because they infringe on the path detail as improved manipulator technology makes finer detail available. Data are included for other thicknesses, ranging from 0.025 in. to the maximum cuttable thickness which is about 0.5 in. at current CO_2 power levels and assuming burr-free, best quality cuts. Thicknesses of 1.0 in. appear feasible when cutting at lower quality levels.

Similar observations are made for the remaining metals. Stainless steel only exhibits best-quality, burr-free cuts up to 0.040 in. while cutting rates are reduced 25% on thin material and 50% as the maximum thickness is approached. Good quality cuts can be obtained on thicknesses up to 0.120 in., and it is possible to penetrate as much as 0.5 in. of stainless steel using multikilowatt CO_2 technology. Cut face roughness values are 100% greater than those for carbon steel but approach those of carbon steel as the roughness values for both metals increase and the maximum, cuttable thickness is approached. Fewer comparisons can be made from available aluminum and titanium data. Aluminum cutting speeds are reduced 50% on thin material and more than 75% on thick. Titanium reacts with the oxygen or air cutting gases and thus cuts more rapidly than carbon steel--25% to 50% as the maximum cuttable thickness is approached. Maximum cuttable thickness is estimated to be 0.08 in. for good quality with a maximum penetration capability of 0.25 in. at available CO_2 power levels. Dross is present in all aluminum cuts, although certain recently marketed CO_2 pulsing options are reported to minimize dross. Titanium can be cut with good quality up to 0.75 in.

Reported data regarding cut face roughness, kerf width, and heat-affected-zone (HAZ) are not complete, but aluminum appears to have a rougher surface, deeper HAZ, and wider kerf width than carbon steel.

A review of composite cutting revealed little systematic speed or quality data, suggesting that the technology is just emerging, possibly because the materials themselves are changing rapidly. Of interest was the observation by one experimenter who has compiled a number of CO_2 and Nd:YAG results that Nd:YAG might be the technology of choice.

Laser Beam Sources. This portion of the review looks at the types of lasers that have been adopted by industry for production cutting of metals and nonmetals. CO_2 technology dominated the cutting field for many years. CO_2 lasers were powerful and their beams were most readily absorbed by nonmetals, particularly organics. The Nd:YAG technology with its low power and poor beam quality was used only on a few superalloys or where highly reflective metals were involved. The review revealed that CO_2 pulsing modes have become sufficiently sophisticated and challenge Nd:YAG technology on reflective metals. CO_2 lasers have also met the demand of modern manipulators for multikilowatt beams that can operate either CW or pulsed on command as the beam progresses from simple trimming operations to the production of detailed cutouts in a single path.

However, the study found it necessary to place equal emphasis on Nd:YAG technology in recognition of several reported trends:

(1) There is an increasing tendency toward short-cycle cutting applications, such as trepanning holes, where the economic impact of the slower Nd:YAG cutting speed is reduced in the presence of proportionately longer fixturing and cut-cut movement cycles on the workpiece.

(2) The near-infrared Nd:YAG beam can be transmitted through flexible light pipes that use available quartz fiber technology. Fiber optic beam delivery greatly simplifies system design where the laser beam must be brought to the work over long distances and into restricted spaces.

(3) Nd:YAG power levels are approaching those of the kilowatt-level CO_2 lasers.

(4) The improved beam quality of "slab" laser configurations that use Nd:YAG technology may be available shortly. One such unit is reported to be under evaluation in industry.

(5) There is some belief that Nd:YAG may be a better choice than CO_2 to cut some composite materials involving inorganic components--notably metals or graphite.

The study reviews commercially available CO_2 and Nd:YAG configurations. Three CO_2 configurations are discussed. The tubular slow-axial-flow lasers are reported to have excellent beam quality but are very bulky and operate only up to a 500 W limit (with a few exceptions at 800 W and 1000 W). More power can be gained while retaining the optical properties of the axial- flow lasers by adding blowers capable of operating at low pressures and high pressure differentials to increase the flow rate of the lasant gas mixture. Fast-axial-flow technology dominates laser design in the 500-3000 W range, and a few examples are commercially available below 500 W and up to 7000 W. The complexities of blower can be eliminated by substituting a short boxlike structure for the tubes and using low pressure fans. Such configurations are available at power levels up to 25,000 W and are called fast-transverse-flow lasers. Several options for pulsed beam CO_2 operation are now available in addition to CW operation:

(1) Gated (or chopped) pulsing for controlling power to complex cuts.

(2) Super pulsing where an enhanced spike of power is added to the leading edge of the simple gated pulse form in order to break down reflectivity.

(3) Spiked pulse using only the enhanced spike, used for drilling where the work is moving past the beam at very high rates of speed.

(4) Hyper pulse wherein an enhanced spike is added to the sustained heating capability of a CW beam. This technique has been effective in producing low-dross aluminum cuts.

Axial-flow lasers are now available with two types of discharge. Longitudinal (DC) discharge has the longest track record on both slow- and fast-flow lasers but requires a high voltage and some turbulence. Induced turbulence adds to the pumping requirements on fast-flow systems. RF discharge avoids both of the foregoing problems and may also reduce gas contamination since electrodes that may erode are outside of the gas envelope in RF systems. RF systems appeared in commercial lasers only a few years ago.

The study also observed a broadened range of options in Nd:YAG technology. Manufacturers now offer:

- Nd:YAG lasers that are optically modified to produce high beam quality at reduced power levels for precision drilling and trepanning.
- Nd:YAG lasers with multiple crystals that produce typical multimode/high divergence beams but which can produce a kilowatt of power.
- Nd:YAG lasers with a conventional low-cost single crystal configuration that has been available for many years at an average power level of about one half a kilowatt.

CO_2 optical materials are reviewed since three are available and none are similar to the quartz optics used in Nd:YAG lasers and systems. The need for circular polarization in CO_2 lasers was noted as was the emergence of non-circular nozzle configurations and pressure-resistant cutting head optics when using increased auxiliary gas pressure.

Two emerging laser technologies, slab/Nd:YAG and excimer, are briefly reviewed. Although neither is available in the commercial range of interest in this review, each foreshadows potential important changes in the state-of-the-art.

- Slab lasers hold the promise of improved beam quality and power without sacrificing the compactness and optical characteristics of conventional rod-type Nd:YAG lasers.
- Excimer lasers are being evaluated to determine if their beam cuts plastics in a nonthermal way, thus reducing thermal damage.

The survey has noted a 400% increase in the number of machine tool builders that have entered the laser system field in recent years. In parallel with this growth is an expansion of manipulation technology.

<u>Laser Beam/Work Manipulators</u>. Recent publications tend to emphasize only those sophisticated machine tool-like systems that feature multiaxis NC path/power programming. This review delineates a separate level of sophistication by also describing industrially significant systems where the cut path is not programmable. Such systems may emphasize workpiece feeding to satisfy typically short cycles and may time-share the laser beam among work stations to enhance flexibility and efficiency. These systems are termed

Level 1 to designate their simplicity. Level 2 systems are those that utilize computer technology for path programming.

Within the Level 2 family are three types of systems:

- Type 1: Beam stationary while workpiece moves
- Type 2: Workpiece stationary while beam moves
- Type 3: Hybrid or combined systems where both optics and work move on programmable axes.

In its two-axis form the Level 2, Type 1 system represents the well-established flat stock cutter. Three- and five-axis variants where cylindrical workpieces are rotated are also used. The desire to apply attractive laser cutting processes to a broader range of workpieces has led to multiaxis systems where flimsy three-dimensional noncylindrical workpieces can be statically fixtured while the cutting process moves over their surface. These Level 2, Type 2 systems are sometimes called "flying optic systems." As such, they require complex optical trains or, in the special case of lower power Nd:YAG systems, light pipes of quartz fiber. Additionally, flying optic systems involve moments when one axis is moving at extremely high velocity to maintain constant path speed. Such speeds have led to the present adoption of a gantry robot configuration as opposed to articulated robots. The gantry robot also provides a larger work envelope while remaining within the tight stability of motion limits that contemporary manipulators offer. Path tolerances of 0.004 in. within a 10 m (total) envelope are cited. Moreover, gantry robots require the least floor space for a given worktable area. The gantry configuration, however, presents a cage-like barrier to the rapid loading and unloading of workpieces such as automobile bodies or body subassemblies. A Level 2, Type 3 system has emerged wherein the worktable moves under a stationary bridge that supports the remainder of the flying optic axes. Floor space is increased in the direction of the worktable, but material handling is reported to be simpler.

Rotational axes in the flying spot stationary work system have led to optical joints that permit the beam to be swept through an arc under control of the NC program. The simplest systems have only one joint but leave the beam (tool point) offset from the path. The computer and special software

accommodate this condition. A less complex computational scheme can be used, but additional optical joint must be employed. Each added bend in the beam path makes alignment more difficult.

An additional axis is discussed. This short-stroke axis moves the cutting head toward or away from the work to accommodate variations in the location of the work surface. Two variations are set forth:

- Gra`ty heads which can only be used for downhand cutting. They operate from a preset hardened ring or roller that contact the work surface.

- Proximity sensors that can operate in any position but are more complex. Electrical fields, probe motion, or light are in use according to the review.

Illustrations of the various types of manipulator and diagrams of some of the optical trains are included in the review.

Conclusions. In tabulating the various procedures and delineating the hardware options, several conclusions become apparent. These conclusions relate to characteristics of the state of the art in the future as follows:

(1) There should be a continuing emphasis on the pulsed CO_2 technology.

(2) Interest in Nd:YAG technology should be supported by new developments in fiber optics and slab lasers. The conviction that Nd:YAG may supplant CO_2 in some composite applications is also cited in support of this conclusion.

(3) Manipulator design of the flying optic system will be influenced by the availability of lightweight, compact lasers and light pipe systems.

(4) Process technology improvements will concentrate on reduced roughness and narrow kerf as manipulators and their controls gain the ability to produce increasingly finer detail on laser-cut parts.

1. INTRODUCTION

The use of lasers to cut materials accounts for more than half of the industrial application of this relatively new technology.[1] According to estimates made in 1981, lasers were being used to cut $900 million worth of products each year.[2] Cutting systems introduced onto shop floors since that time have undoubtedly raised this annual laser cutting output to over a billion dollars.

This increase in industrial importance has been accompanied by a significant improvement in the state-of-the-art (SOA) performance of the laser cutting process. For example, "good" quality edge finish in 1967 was any surface roughness value less than 2000 μin. (Rt). Today, finishes of 100 to 500 μin. are common.[3] Of particular interest to the aerospace industry is the fact that laser cutting reduces by a factor of 10 the amount of thermally disturbed material that must be machined away. Only a few thousandths of an inch may be involved under today's SOA practices. At the same time, systems have evolved that can apply five- and six-axis cutting to assemblies almost as large as an automobile. System controls can follow cutting paths within a few thousandths of an inch while producing such path detail as inside corners with 0.003 in. radii. All of this can be applied to a part directly from engineering information. Path programming directly on the part, using advanced software to minimize the points that must be identified, is also possible.

REFERENCES

1. Seaman, F. D., "Assessment of Materials-Processing Lasers," EPRI Report No. EM-3465, prepared by IITRI for Electric Power Research Institute, 3412 Hillview Ave, Palo Alto, California 94304, May 1984, pp. 4-11.

2. "Biggest Laser Mart in Metal Working," American Metal Mart/Metalworking News, December 15, 1980.

3. Schwartz, M. M., "Laser Welding and Cutting," Weld. Res. Counc. Bull. No. 167, 1971, 34 pp.

2. PURPOSE AND SCOPE

In reviewing the rapidly advancing laser cutting SOA, this study will first (Section 3) set forth the cutting performance standards that define contemporary process technology. Section 4 describes lasers that represent SOA beam technology. Such lasers are essential to the achievement of contemporary process performance standards. Section 5 covers the most rapidly advancing facet of laser cutting technology--the mechanical manipulator system. Advances in this area have stimulated the overall growth of the process by bringing its constantly improving performance to a broader spectrum of parts, with increasing accuracy and ease of application. This approach to the subject has been adopted to provide prospective users with an idea of what to expect from a laser cutting application and to emphasize the close relationship between such expectations and the types of products that are available to achieve it.

The focus is on progressive, full-thickness cuts in materials such as those listed in Table 2-1.[1] Percussive, static hole drilling. and partial penetration marking/trimming raise significantly different issues and deserve separate consideration. For example, in percussive drilling, real-time control of beam parameters is important. In cutting, the emphasis is on path control. For drilling applications manipulators emphasize point-point movement instead of contour-path-following capabilities. Marking processes differ greatly from full penetration cutting technology. Cutting process technology is dominated by the need to produce a smooth, dross-free cut face while the marking consists of a series of precisely placed shallow pits where surface finish and dross are not usually issues.

TABLE 2-1. MATERIAL RATINGS FOR CUTTING WITH INDUSTRIAL LASERS

Material	Ease of Cutting[a]
CO_2 Laser Cutting	
Stainless Steel (300 series)	(F-G)
Stainless Steel (400 Series)	(G)
Galvanized Steel	(G)
Carbon Steel (Low)	(E)
Carbon Steel (Medium)	(E)
Carbon Steel (High)	(G)
Steel, Free Machining	(P)
HSLA	(G)
Coated	(G)
Spring Steel	(E)
Titanium	(G)
Hastelloy "X"	(G)[b]
Copper	(F-G)
Brass	(P-F)
Aluminum	(P-F)
Tantalum	(F)
Ceramic (Aluminum Oxide)	(G-E)
Polyethylene	(E)
Polycarbonate	(F)
Acrylic	(E)
Delrin	(E)
Nylon	(E)
Wood	(G-E)
Plywood	(E)
Fiber Glass	(P-F)
Laminates	(F-G)
Glass	(G-E)
Rubber	(F-E)
Leather	(E)
Paper	(E)
Solid State Laser Cutting	
Stainless Steel (300 series)	(G)
Carbon Steel (Low)	-
Carbon Steel (Medium)	(F-G)
Carbon Steel (High)	(F-G)
Gold	(G)
Aluminum	(G-E)
Tantalum	(G-E)
Nickel Silver	(G)
Molybdenum	(G)
Ceramic (Aluminum Oxide)	(G-E)
Plastic	(P-F)

[a]P = Poor, F = Fair, G = Good, E = Excellent.

[b]Added from other sources.

REFERENCES

2-1. Ruselowski, J. M., "Laser Selection for Cutting," Proceedings of Conference on Lasers in Manufacturing: S-P-O-T '87, Los Angeles, Calif., March 24-26, 1987; published by Society of Manufacturing Engineers, Dearborn, Mich.

3. STATE-OF-THE-ART LASER CUTTING PERFORMANCE

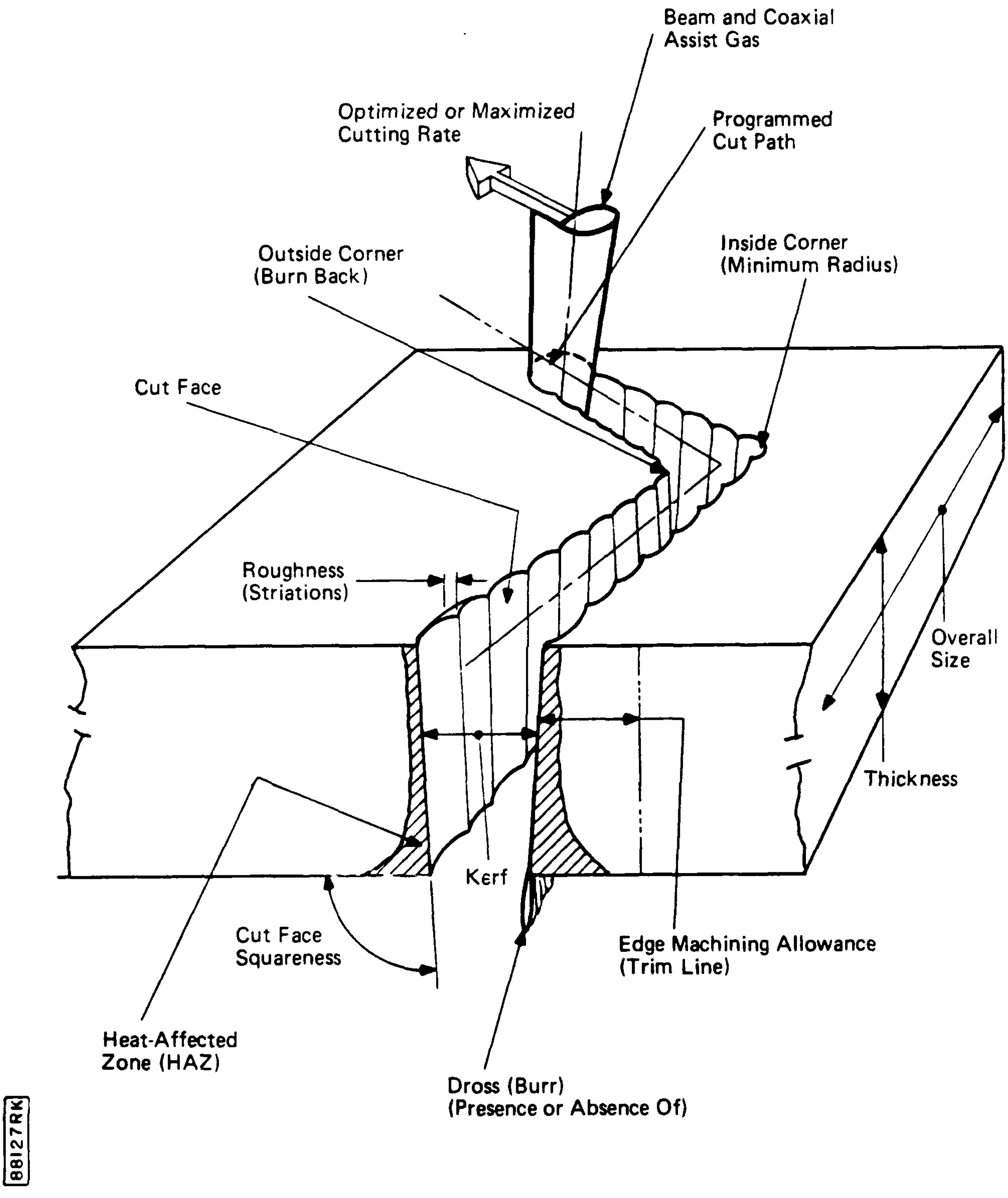
Figure 3-1 characterizes the elements of a full-penetration laser cut. The achievement of these qualities defines the performance of the cutting process.

A number of materials can be cut, as shown by the extensive listing in Table 2-1. However, certain materials were chosen for emphasis in Section 3 because they are of interest to the defense manufacturing community and enough data are available to document a state-of-the-art (SOA) cutting performance level. Additionally they tend to represent other, lesser known cutting applications. The selected materials are as follows:

- Carbon and alloy steels
- Austenitic stainless steels and nickel-base high-temperature alloys
- Aluminum
- Titanium
- Nonmetallics (plastics and composites).

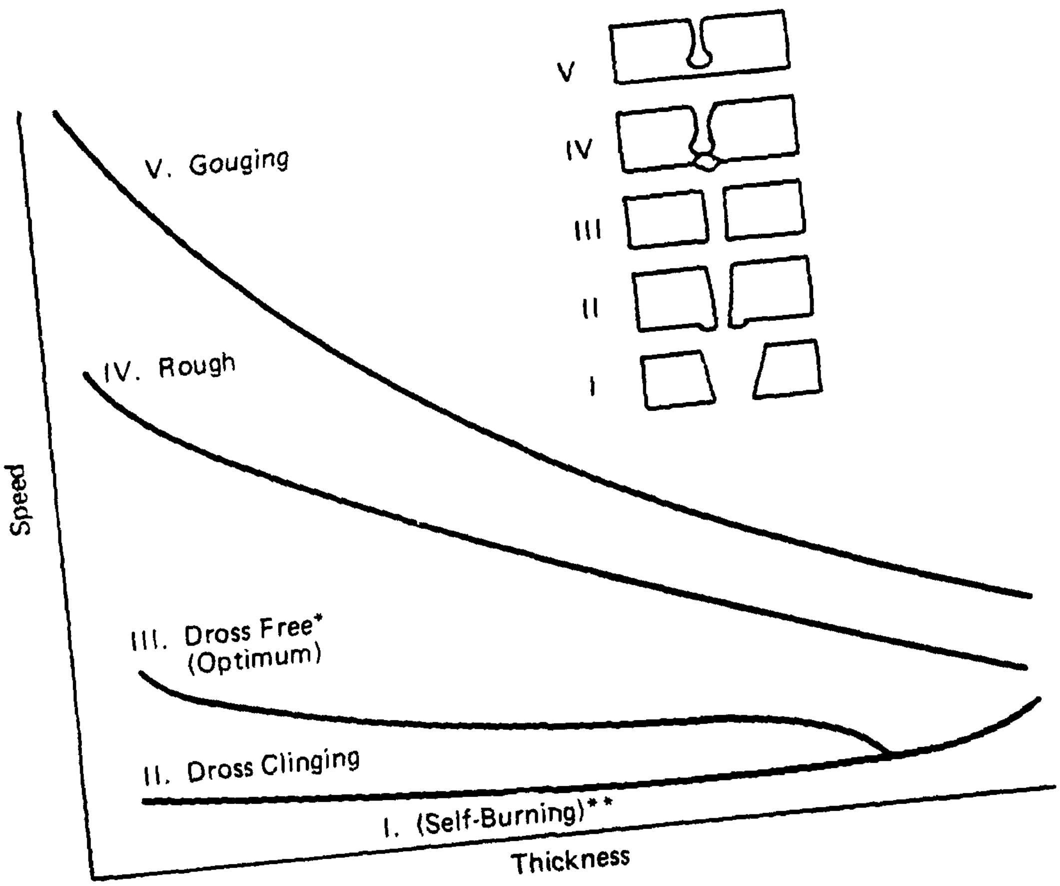
The cutting mechanism for nonmetallic composites and all plastics is the result of direct evaporation of materials from the kerf. Metals, in contrast, are cut by some combination of melting and metal expulsion by a stream of gas. Metals may also exhibit an exothermic reaction with the stream of gas. Where this occurs, the reaction can exceed the heating capability of the laser. Thus the behavior of the various materials is different for a given set of laser cutting conditions, and the process performances listed below are understandably different.

Performance also depends upon the process itself. Arata et al.[1] have noted (Figure 3-2) that cut qualities (kerf width, cut face roughness, cut face angle, and the presence of recast metal on the cut face or lip) all vary with speed and thickness for any given power. In selecting values to represent the SOA, an attempt has been made to choose those representing mode III (optimized) or mode IV (maximized) in Figure 3-2.



Source: IITRI Laser Center

Figure 3-1. Cut qualities.



* Not all materials exhibit type III behavior.

** For reactive metals such as carbon steel and titanium.

Adapted from Arata et al.[1]

88128RK

Figure 3-2. Cut quality relationship to speed and thickness.

Laser manufacturers[2] report that refinements on a case-by-case basis in the field have often resulted in a 20% improvement in speeds and quality levels over the SOA levels cited in this study and encountered in their own laboratories. This observation relates principally to carbon and stainless steel production cutting operations.

Performance further depends upon cutting technique employed. In the following discussion, most of the data are for carbon dioxide (CO_2) lasers using a coaxial gas nozzle and operated in the continuous wave (CW) output mode using 2.5 in. focal length antireflective (AR) coated transmission optics. There is a trend for complex part shapes toward longer focal lengths such as 5 and 7 in. Tolerance to focus distance variation increases markedly as focal length increases, but focusing sharpness drops off somewhat.[2]

There is also a trend toward a pulsed application of power. Pulsing is an attractive method for delivering an appropriate level of peak (penetrating) power to a cut while reducing the average power. Reduced average power prevents burning as manipulators slow down to accommodate complex shapes or encounter features that overheat easily (see Figure 3-1).

Pulsed CO_2 data are included where noted. Also given are neodymium:yttrium-aluminum-garnet (Nd:YAG) pulsed cutting data because the technique is considered vital in meeting the detailed precision cutting requirements of the defense (aerospace) industry and Nd:YAG can be used with fiber optic beam manipulation while CO_2 cannot.

3.1 STEEL

The CO_2 laser, with oxygen as an assist gas, has been the conventional tool for cutting carbon steel, high strength steel, and cast iron because it has been available for several decades at multikilowatt power levels that result in commercially attractive speeds.

3.1.1 Cutting Rate

Table 3-1 is a compilation of cutting rates that represent optimized cut quality.[3-7]

The two modes of power application are shown. The traditional continuous application of power (CW)) provides one set of data. More recently, multikilowatt pulsed CO_2 lasers have become available. Introducing pulses into the

TABLE 3-1. OPTIMIZED[a] CUTTING SPEEDS FOR CARBON STEEL[3-6,9] (O_2 Assist)

Thickness, in.	Speed, (ipm) CO_2/CW 1200 W (Refs. 3, 5)	CO_2/Pulsed 750 W (Ref. 4)	CO_2/CW 500 W (Ref. 4)	CO_2/Pulsed 500 W (Ref. 6)	Nd:YAG/Pulsed 400 W (Refs. 3, 9)
0.025	440	390	ND	ND	ND
0.040	340	265	160	132	38[b]
0.080	245	-	100	60	16-24
0.120	152	86	60	24	10-18
0.160	100	60	ND	ND	8-13

ND = no data; does not imply not possible.

[a]For best cut surface finish, kerf, and HAZ.

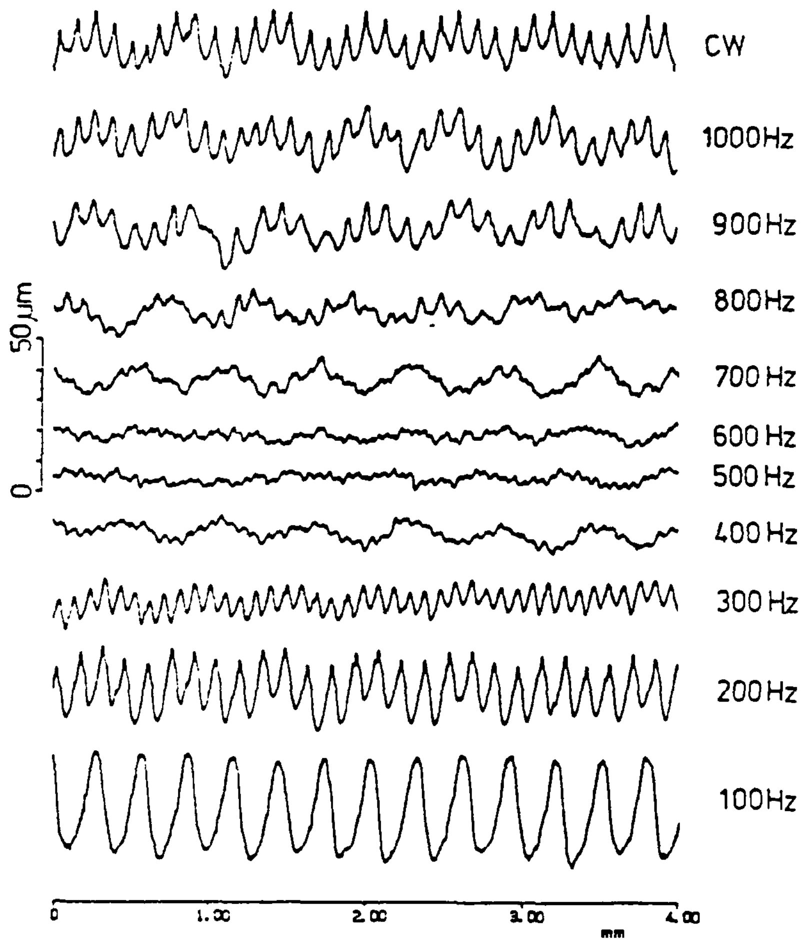
[b]Values represent O_2 (30 psig) and shop air (80 psig) as alternative assist gases.

process creates more striations, which are shallower and result in less surface roughness.[8] Further, the metal in which they are formed sees less heat. Less heat means that the process forms less surface oxide contamination (dross) and the material behind the cut face experiences less heat effect[8]--i.e., has a smaller heat-affected zone (HAZ).

The reduced CO_2 cutting speeds by pulsing may limit commercial value where long profiling cuts are to be made. However, many small complex cutouts involve only a short cutting cycle dominated by long movement from cutout to cutout so that cutting speed is less important. The progressive cutting of hole shapes (trepanning) is a commonly encountered example. Nd:YAG is also used in such situations, and Nd:YAG data[9] are listed in Table 3-1.

3.1.2 Surface Roughness

Table 3-2 lists roughness values for the two procedures and several thicknesses described in Table 3-1. Figure 3-3 illustrates the potential for influencing surface roughness[8] by applying the power in a pulsed manner. Organizations familiar with various types of lasers,[2] note that the Figure 3-3 results cannot always be transferred to all cutting situations and that the configuration of the laser can play an equally powerful role in surface finish (see Section 4 for a description of laser configurations). The state of the art has now reached a point where laser cuts can compete with die cutting in



Source: Loughborough University of Technology, U.K.

Figure 3-3. Effect of pulsing on roughness of cut surface.

TABLE 3-2. TYPICAL SURFACE ROUGHNESS VALUES FOR CARBON STEEL[5,6] (CO_2/O_2 Assist)

Thickness in.	Roughness (Rt),[a] μin. 1200 W/CW (Ref. 5)	500 W/Pulsed (Ref. 6)
0.025	700	100
0.040	800	120
0.080	1080	190
0.120	1320	360
0.160	1600	400

[a]Converted to Rt (approximate) by multiplying Ra by a factor of 2.

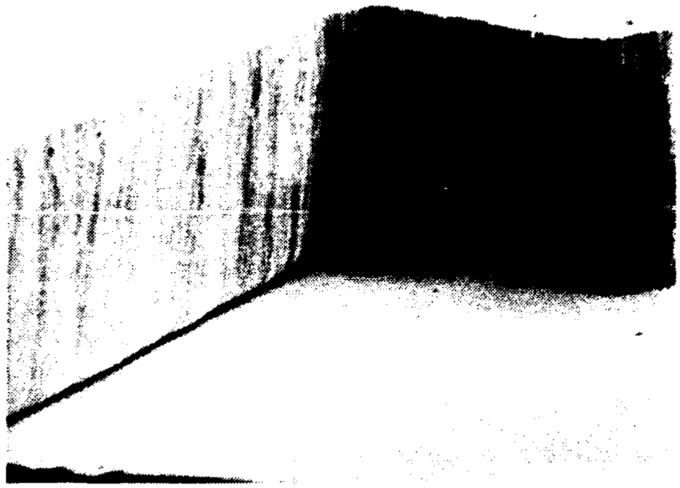
such critical applications as the fabrication of generator laminations.[7] Figure 3-4 shows the surface of one such cut, and Figure 3-5 illustrates the roughness profile. The roughness value (Rt) appears to be about 200 μin.). (0.0002 in.).

3.1.3 Kerf Width

The advent of manipulators (see Section 5 for a discussion of them) that are capable of following abrupt changes of direction in the programmed path meant that the width of the kerf became the limiting factor in establishing the radius on inside corners. The inside corner is commercially important because laser cutouts are often substituted for mechanical punching where sharp radii are difficult to maintain on tools. Kerf width is a strong function of laser spot size and the distribution of energy within the spot. Both factors have improved over the years. Kerf width increases with thickness as shown in Table 3-3.

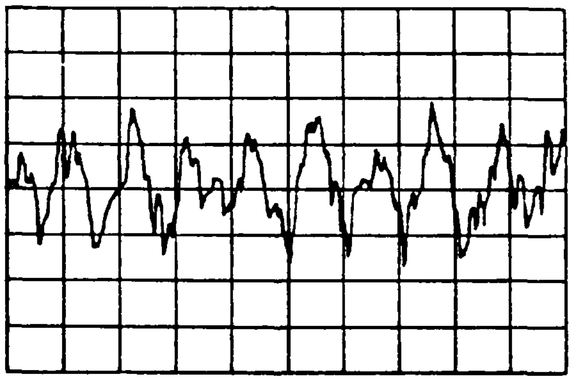
3.1.4 HAZ

As previously noted, the increasing use of pulsed processes, using both Nd:YAG and CO_2 technologies, has reduced the heating of the metal in cutting procedures. Evidence of this can be found in the greatly reduced volume of metal behind the cut face that has sustained heat damage. The values for carbon steel are given in Table 3-4. Both sets of values were determined from microhardness traverses in a hardenable grade of steel.[4,11]



Source: Lumonics, Laserdyne Products

Figure 3-4. Scanning electron micrograph of a section of a laser-cut rotor lamination.



Vertical: 94.2 μin./division
Horizontal: 0.015 in./division

Source: Lumonics, Laserdyne Products

Figure 3-5. Roughness profile of a typical laser-cut edge of a rotor lamination. Plot shows height of edge striations as a function of position along surface.

TABLE 3-3. MINIMUM KERF WIDTHS IN CARBON STEEL[3,6,10]
(CO_2/O_2 Assist)

Thickness, in.	Kerf[a] Width, in.
0.06	0.004[b]
0.09	0.006[c]
0.125	0.008[b]
0.250	0.012[d]

[a]Kerf increases linearly with thickness (Ref. 6).

[b]Ref. 6.

[c]Ref. 10.

[d]Ref. 3.

TABLE 3-4. TYPICAL HAZ VALUES FOR CARBON STEEL[4,11]
(CO_2/O_2 Assist)

	HAZ, percent of thickness	
Thickness, in.	CW[a] 1975 (Ref. 11)	Pulsed, 1985-86 (Ref. 4)
0.025	100	10
0.040	86	7
0.080	56	6
0.120	13	5
0.160	-	3

[a]Value can sometimes be reduced further by increasing gas flow.

The HAZ has particular significance in the fabrication of components for defense products that are subject to fatigue. Fatigue performance is sensitive to edge integrity and stress state. As a consequence, many defense fabricating specifications require that an edge machining allowance (EMA) be added to all dimensions on thermally cut parts, to be removed later by a machining operation. In high strength steels the removal of large amounts of

material suggested in Table 3-4, center column, represents a significant machining cost. If the EMA could be reduced concomitantly with the values in the right-hand column, the cost of EMA removal along the edges of large panels and forgings could be greatly lowered.

3.1.5 Burr Formation

The presence of a burr after cutting may be undesirable and requires a costly secondary operation to remove. Burr formation depends on several factors. As cutting progresses in any material, the assist gas sweeps molten dross from the face of the cut. This dross is a mixture of melted base metal and any compounds formed by reaction with the assist gas. Whether this dross can be swept away or whether it hangs on the lower lip of the cut depends on its fluidity and the temperature of the cut face among other factors. These factors, in turn, depend on the material being cut. However, burr formation can also be influenced by the cutting procedure. In Figure 3-2, dross appears to form a severe burr under zone II and IV cutting conditions. The formation of a burr can also be influenced by focal point position in the metal.[4]

However, if the above procedure requirements are met, burr-free carbon steel cuts can be made over a wide range of thicknesses (0.03 to 0.25 in.).[6]

3.1.6 Maximum Thickness

As thickness increases, desirable performance qualities are sacrificed. Therefore, delineation of maximum cut thickness may depend on how much sacrifice is acceptable. For 1000 to 1200 W/CO_2 systems operating in a "low order" or "basic" mode, Table 3-5 suggests that the upper limit for carbon steel is about 0.5 in. A significant restriction reported on focal point placement[4] suggests a maximum workpiece thickness of 0.480 in. When cut quality is not so important, workpiece thicknesses of 1.00 in. are apparently feasible.

3.2 AUSTENITIC STAINLESS STEEL AND HIGH-TEMPERATURE ALLOYS

In spite of its similar sounding designation, austenitic (e.g., AISI type 304) stainless steel presents a cutting challenge much different from carbon steel. In fact, its relative insensitivity to oxygen as a cutting gas, its viscous flow characteristics in the presence of assist gases, and low thermal diffusivity place its cutting behavior much closer to such high-temperature alloys as the Inconel series.

TABLE 3-5. BURR-FREE RANGES FOR THREE MATERIALS[10]
(O_2 Assist, All Materials)

Thickness, in.	Material[a] Carbon Steel	Stainless Steel	Aluminum
0.04	Burr free	Burr free	Good
0.06	Burr free	Burr free	Good
0.08	Burr free	Burr free	Good
0.120	Burr free	Good	Good
0.180	Burr free	Good	Poor
0.250	Burr free	Good	Poor
0.500	Good[b]	Good	Poor
1.00	Good	Poor	Poor
1.00	Poor[c]	Poor	ND[d]

[a]Data taken from sources that relate to 1000 to 1000 W/CO_2/pulsed systems.

[b]Refers to good cut quality except that a light burr requiring removal can be expected.

[c]Refers to poor cut quality implying heavy recast layers on the surface, a significant burr, and possible erosion.

[d]ND = no data; does not imply not possible.

Although much of the information herein is based on CO_2/CW technology, at least one system designer prefers Nd:YAG for high-precision cutting of aerospace components.[12] Pulsed CO_2 technology is also cited as a means for achieving good surface finish in these alloys.

3.2.1 Cutting Speed

Table 3-6 provides a compilation of cutting rates that represent a maximized procedure using a SOA laser system[4] operating in a low-order mode using O_2. Thus the rate is comparable to that given for carbon steel (CW/O_2 assist technology). The material is an AISI type 304 stainless.

TABLE 3-6. OPTIMIZED CUTTING SPEEDS FOR STAINLESS STEEL[4] (1200 W/CO_2/CW/O_2 Assist)

Thickness, in.	Speed, ipm
0.040	250
0.080	105
0.120	75
0.160	65

3.2.2 Surface Roughness

Optimized (pulsed) surface roughness values in Table 3-7 are comparable to the pulsed values given for carbon steel.

TABLE 3-7. TYPICAL SURFACE ROUGHNESS VALUES FOR STAINLESS STEEL)[6] (500 W/CO_2/Pulsed/O_2 Assist)

Thickness, in.	Roughness (Rt),[a] μin.
0.025	200
0.040	300
0.080	350
0.120	400
0.160	440

[a]Converted to Rt (by multiplying Ra by a factor of 2).

3.2.3 Kerf Width

No data are available.

3.2.4 HAZ

No published data are available. However, EMA values are frequently encountered for aerospace application in this class of alloys. The existence of these values indicates that some deterioration in fatigue strength has been observed in thermally disturbed material directly behind the cut face. Allowances are similar to those cited for high-alloy steel so that the HAZ

values for carbon steel in Table 3-4 may also be relevant for stainless steel. The allowance for these materials is often twice that required for aluminum alloys.

3.2.5 Burr Formation

The thickness range over which one can expect burr-free cuts is not as great as that encountered in carbon steel (see Table 3-5). One investigator[1] noted that laser-cut stainless steel exhibited a pronounced layer of cracked, porous oxide-bearing dross on the surface when oxygen was used. The recast layer was oxide free when argon was used as an assist gas.

3.2.6 Maximum Thickness

According to Table 3-5, the maximum thickness for burr-free stainless steel cuts (at the 1200 W level of power assumed in this evaluation) is only 0.080 to 0.120 in. However, "good" quality cuts can be made up to 0.5 in. and "poor" quality cuts may approach 1.0 in.

3.3 ALUMINUM AND ALUMINUM ALLOYS

Aluminum and copper are often listed as hard to cut because of their tendency to reflect the laser beam. Unlike the situation with carbon steels, oxygen does not provide added heat that might offset the reflectivity. Melting the refractory oxide that forms also takes heat away from the cutting process.[13] However, as the laser power level approached 1 kW using CO_2 technology, the cutting of aluminum and its alloys acquired early commercial significance, particularly in the aerospace industry,[14] in spite of relatively low absorption for the CO_2 wavelength. Laser trimming of formed aluminum parts is now frequently encountered.

3.3.1 Cutting Speed

Table 3-8 is a compilation of cutting rates that represent a maximized procedure using a SOA laser system. Oxygen is the reported cutting gas. However, helium has also been used to produce cutting rates similar to those obtained with oxygen.[13] Air is recommended over O_2 and inert gas.[9]

TABLE 3-8. OPTIMIZED CUTTING SPEEDS FOR ALUMINUM[3,6,9]

Thickness, in.	Speed, ipm		
	$CO_2/CW/O_2$ Assist (Ref. 6)		Nd:YAG/Pulsed/Air Assist[a] (Refs. 3, 9)
	2000 W	1000 W	400 W
0.014	ND	493	ND
0.025	ND	305	60
0.040	240	175	32-55
0.080	120	45	14-16
0.120	60	25	8-9
0.250	ND	ND	2

[a]Air recommended over O_2 and inert gas with respect to cut cleanliness.[9] Inert gas is slower than air while oxygen gives faster cuts.

[b]ND = no data; does not imply not possible.

It is often assumed that the reflectivity of aluminum demands high laser power levels. Such levels suggest multikilowatt CO_2 technology[6]. However, as previously noted, where the cut path is short and the laser is only used over a short portion of the floor-to-floor cycle, the lower power, lower cost Nd:YAG technology may be acceptable. Nd:YAG cutting rate values have been included in Table 3-8.

3.3.2 Surface Roughness

Table 3-9 provides limited data regarding surface roughness, which appears to be 500 to 800 μin. Rt. For comparison, Table 3-2 lists a 1080 μin. surface roughness for oxygen-cut, CW, carbon steel at the same thickness.

Table 3-2 also lists a 190 μin. roughness for pulse-cut carbon steel. Thus it is possible that introduction of pulse technology could reduce the Table 3-9 roughness values. However, most aerospace applications require the removal of thermally damaged material in any event so that the finished part may often have machined edges and post-cut roughness is not important. Under such conditions the depth of the HAZ may be more significant since it governs the edge machining allowance that must be machined away.

TABLE 3-9. TYPICAL SURFACE ROUGHNESS VALUES FOR ALUMINUM ALLOYS 1200 W/CO_2/CW/O_2 Assist)

Thickness, in.	Roughness (Rt),[a] μin.
0.080	560-800[b] (Ref. 13)
0.300	520[b,c] (Ref. 6)

[a]Converted to Rt by multiplying Ra by a factor of 2.

[b]No significant difference between cuts using O_2 or air as an assist gas.

[c]Alloy not specified.

3.3.3 Kerf Width

Reference 13 reports 0.010 to 0.014 in. kerf widths in 0.080 in. thick sheet for both O_2 and air cutting (1 to 2 kW) using a 0.01 mm beam. There is evidence that helium produced slightly narrower widths within the above range. All of the above widths are slightly narrower than those reported for steel.

3.3.4 HAZ

The depth to which thermally disturbed material exists governs what happens to laser-cut edges after they are cut. Thermally disturbed material exists to the depths shown in Table 3-10.[13] Table 3-10 further suggests that increasing the cutting rates can reduce the HAZ by a factor of 10 if helium is used. Helium avoids the formation of oxide with its attendant heat. Helium may also provide some added chilling because of its high specific heat. The resulting HAZ of 0.001 in. suggests that post-cut material removal and its cost can be reduced substantially if the above changes are made in the process.

3.3.5 Burr Formation

Table 3-5 suggests that aluminum cannot be cut without some burr formation from the dross (metal-oxide mixture) as it is blown out of the bottom of the kerf. Systematic exploitation of parameters in Reference 13 suggests, however, that a range of process speed can produce a "dross-free"

TABLE 3-10. TYPICAL HAZ VALUES FOR ALUMINUM[13]
(CO_2/CW, 1.2 mm Sheet Thickness)

Speed, ipm	HAZ Thickness with Given Gas, inches from cut face[a] O_2	He
120[b]	0.01	0.01
960[c]	0.005	0.001

[a]Based on elevation of hardness above base metal.
[b]Would also produce relatively good surface finish e.g., 500 μin. Rt).

[c]Would produce maximum surface roughness (e.g. 800 μin. Rt).

cut at 1 to 2 kW in the materials evaluated even though O_2 was used (0.480-0.80 in. thick 7075 Alclad aluminum)). Dross-free conditions only existed over something less than one-third of the cutting range even though oxygen was used as the assist gas.

3.3.6 Maximum Thickness

If maximum thicknesses were based on burr-free cutting, as it was in carbon steel, it would be difficult to assign a value greater than the 0.08 in. thick material evaluated in Reference 13 even though power levels up to 2 kW (CO_2/CW) were available. If, however, "good" quality (with some burr) is acceptable, Table 3-5 indicates that useful cuts could be made in thicknesses up to 0.120 in. The cutting rates listed in Table 3-8 suggest the acceptance of 0.25 in. as the maximum thickness for aluminum according to Nd:YAG data.

3.4 TITANIUM

The interaction of oxygen and titanium produces large quantities of heat. The role of oxygen as a cutting gas is considerably more prominent for titanium than is the case with carbon steel.

3.4.1 Cutting Speed

Table 3-11 lists typical maximized cutting values for titanium for CO_2 (1000 W) and Nd:YAG (400 W). Compared to Table 3-1 rates, titanium cuts 50 to 130 ipm faster than carbon steel for a given thickness using the higher speed

TABLE 3-11. OPTIMIZED CUTTING SPEED FOR TITANIUM[6,9]

Thickness, in.	Speed, ipm: $CO_2/CW/O_2$ Assist 1000 W (Ref. 6)	Nd:YAG/Pulsed/Air Assist[a] 400 W (Ref. 9)
0.025	570	42
0.040	420	37
0.080	285	28
0.120	225	22
0.160	180	15
0.200	150	11
0.250	125	8

[a]Oxygen is not recommended for production cutting in this reference, possibly because it results in excessive burnback at the slow cutting rate.

CO_2 technique. Such information might be considered important for high-volume production or where long cut path lengths are considered (as in profile cutting of large panels in aerospace components).

3.4.2 Maximum Thickness

A projection of Table 3-11 cutting speeds suggests that the maximum thickness for 1 kW might be about 0.5 in. However, Reference 3-14 shows a 1.5 kW cut in Ti-6Al-4V alloy that is 0.75 in. thick. Surface finish on this thicker cut would be considered "good" based on criteria from preceding discussions.

3.5 ORGANIC MATERIALS--PLASTICS

More than 40 families of plastics are commonly encountered in industry, not including the growing number of multicomponent materials called composites (which are covered in Section 3.6). The monolithic organic plastics vary among themselves, and fall into two broad categories. Those plastics that soften and melt upon heating are called thermoplastics. Other plastics resist heat and are called thermosetting.[15] Performance during laser cutting is greatly influenced by the category of the plastic being cut.

Plastics readily absorb the infrared (10.6 μm) radiation produced by the CO_2 laser. The 1.06 μm wavelength of the Nd:YAG lasers is not as readily absorbed. Conversion of the absorbed energy into heat results in vaporization of the plastic along the cut path so that the cut itself is produced by vaporization while the nature of the cut surface depends upon whether the material is thermoplastic (and melts with some decomposition or "charring") or thermosetting (and simply decomposes). Decomposition is related to the combustibility of the material. As Table 3-12 suggests, naturally occurring organics show a greater tendency to burn and char than do synthetic materials.[12]

TABLE 3-12. COMBUSTIBILITY OF ORGANIC MATERIALS[12]

Low Combustibility	High Combustibility
Acrylics	Leather
PTFE	Wood
Polymethylene Oxide	Wool
Polyethylene	Cotton
Polypropylene	Laminates
Polycarbonate	PVC
Rubber (natural or synthetic)	

Because plastics do not exhibit an exothermic reaction while being cut, the chemical nature of the assist gas is less important. Compressed air and oxygen are commonly encountered.

3.5.1 Cutting Speeds

Table 3-13 sets forth cutting speeds for two dissimilar materials.[2] Acrylic is a thermoplastic material; polycarbonate is a thermosetting organic compound.

3.5.2 Surface Roughness

For plastics the term edge finish is more often used than surface roughness. Vanderwert[15] notes that most of the elements that control surface finishes on metals also pertain to plastics. However, he adds that "for thermoplastic materials a wider range of edge finishes can be obtained by

TABLE 3-13. MAXIMIZED CUTTING SPEEDS FOR TWO PLASTICS[4] (1200 W/CO_2/CW/O_2 Assist)

Thickness, in.	Speed, ipm	
	Acrylic	Polycarbonate
0.160	360	320
0.240	230	200
0.400	165	100
0.800	50	ND

ND = no data given; does not imply not possible.

varying process parameters" and also that "reduced machining rates allow time for adequate melt and flow of the molten plastic. This, coupled with low-velocity airflow results in a smooth, fire-polished edge." This useful type of edge is not observed in metals or thermosetting plastics. Metals conduct heat away from the cut to permit rapid coalescence of any broad area of molten material on the surface. Thermosetting plastics increasingly resist flow as they approach their decomposition temperatures.

Edge finish in plastics is also closely associated with charring tendency. "As charring tendency increases, the visual appearance and edge roughness are influenced by the decomposition deposit," according to Vanderwert.[15] "For a given material thickness the adhesion of the decomposition products decreases with increased charring tendency. With light charring the deposit is totally adhering. However, for materials with severe charring tendency, a portion of the deposit is easily removed."

3.5.3 Kerf Widths

Because plastics decompose at much lower energy densities than metals, kerf width can be varied at will by changing optics to provide a different spot size or by defocusing. However, Vanderwert[15] recommends against increasing the kerf width to more than twice the minimum value. Kerf width increases with increasing thickness. Wall straightness is a reflection of the beam taper and position of the focal point within the work unlike metals where it is a function of speed at some optimum cutting focus.

3.5.4 Maximum Thickness

The ease with which the beam dissociates plastic suggests that maximum cut thicknesses for any given power level would be high. However, other factors limit cut quality on thick material. At very slow speeds charring becomes excessive and there is a tendency toward rounding of the upper and lower edges of the cut. Table 3-13 suggests that speeds will fall below 100 ipm at some thickness between 0.4 and 0.8 in. Thus the maximum practical thickness might also fall in this range.

3.6 COMPOSITES

A composite consists of two or more discrete materials. Wood, with its grain, is a composite. Fiber glass is also a composite, as are materials made with ceramic fibers bonded into a matrix of metal. Composites present a unique challenge to the laser cutting process. A cutting process that is effective on one component of the composite may be ineffective or excessive for the other. The greater the dissimilarity in thermal sensitivity, the more difficult it is to find a suitable laser cutting process. This dissimilarity problem has led to classification of composites into three groups according to their components.[16]

3.6.1 Organic/Organic

Organic/organic commposites are the easiest group to cut. Their behavior is similar to plastics. Kevlar and wood are examples of this group. The CO_2 laser is almost always used because its wavelength is readily absorbed by the materials involved. Table 3-14 gives cutting rates for specific cases.

3.6.2 Inorganic/Organic

The most difficult group to cut is the inorganic/organic composites because of the disparity in the behavior of the materials in a given beam. A nonthermal method such as abrasive sawing or high pressure water jet may be required. Table 3-15 lists cutting speeds for specific cases. Examples of the maximum thickness that can be cut without charring or special laser techniques are given in Table 3-16.

TABLE 3-14. CUTTING SPEEDS FOR ORGANIC/ORGANIC COMPOSITES[16,17]
(CO_2/Air Assist)

Material	Thickness, in.	Speed, ipm: 1500 W CW	1500 W Pulsed	CW 1300 W	CW 500 W	CW 400 W	CW 300 W	CW 250 W
Kevlar	0.040	ND	ND	ND	ND	ND	ND	90[a]
Kevlar	0.93	ND	ND	ND	ND	ND	212[a]	ND
Kevlar	0.120-0.125	ND	ND	ND	ND	90[a] 240	ND	ND
Kevlar	0.250	240[b]	8[c]	30[a]	ND	ND	ND	ND
Plywood	0.75	60	ND	ND	30	ND	ND	ND

ND = No data reported, does not imply not possible.

[a]Ref. 17 data.

[b]Reported as a very clean, char-free trepanned hole.

[c]Some charring reported.

TABLE 3-15. CUTTING SPEEDS FOR INORGANIC/ORGANIC COMPOSITES[16]
(CO_2/CW/Air Assist)

Material	Thickness, in.	Speed, ipm: 5000 W	1500 W	1000 W
Glass/Epoxy (G-10)	0.062	ND	ND	600
	0.250	300[a]	80	ND
Graphite/epoxy (cured)	0.125	ND	80[b]	ND
Graphite/epoxy (uncured)	0.062	ND	3200	ND

ND = no data reported, does not imply not possible.

[a]Reports significant char and fumes from $CaCO_2$ filler in epoxy.

[b]Reports 0.04 in. HAZ.

TABLE 3-16. MAXIMUM THICKNESS THAT CAN BE LASER CUT[16] FOR INORGANIC/ORGANIC COMPOSITES ($1500\ W/CO_2/CW$/Air Assist)

Material	Maximum Thickness, in.
Kevlar	0.4
Graphite/Epoxy	0.4

3.6.3 Inorganic/Inorganic

The inorganic/inorganic composites present less disparity between components than the inorganic/organic group but may require an evaluation of Nd:YAG technology as opposed to CO_2 since some components are more easily processed with the shorter wavelength of the Nd:YAG beam. Specific cutting rates that produced satisfactory results are listed in Table 3-17.

TABLE 3-17. CUTTING SPEEDS FOR INORGANIC/INORGANIC COMPOSITES[16] ($1500\ W/CO_2$[a]/Air Assist)

Material	Thickness, in.	Speed, ipm	
		CW	Pulsed
Boron/aluminum	0.04	320	ND
SiC/titanium	0.032	320	24[b]

ND = no data.

[a]Experimenter notes that Nd:YAG might be a better process for inorganic/inorganic composites, and also notes that a 2.5 in. focal length lens had to be used to get a sufficiently small spot.

[b]Exhibited 0.004 in. matrix meltback plus an 0.02 in. dross "fringe" at the top of the cut.

There is a growing realization that pulsed beams can cut composites with less damage then CW beams.[17] As would be expected, pulsed cutting rates are lower. The lack of systematic process data over a range of thicknesses suggests that the SOA is immature--possibly because the nature of some of the advanced composite materials is changing rapidly.

3.6.4 Condition of the Cut Surface

The cutting of composites does not result in the same surface condition as encountered in metals. In an extensive survey of procedures that maximized cut quality for the particular technique being used, Lawson[17] observed cut surface degradation in two ways:

- Visible destruction such as delamination
- Chemical degradation determined by poking a sharp knife into the cut face and noting the depth of penetration for a given load.

Table 3-18 establishes a matrix of selected materials versus the several laser procedures explored, and introduces the quantitative observations made by Lawson. In spite of gaps in the data, a preliminary picture of the state of the art emerges with respect to the issue of cut edge quality. In reviewing the results Lawson noted that:

- Organic/organic materials (Kevlar) cut best because of low conductivity and dissociation temperature.
- Inorganic/organic materials (glass/epoxy and graphite/epoxy) were much harder to cut because of dissimilarity of components. Glass/epoxy was somewhat easier to obtain a good cut in than graphite. Graphite also conducts heat more deeply into the material away from the cut edge.

Several other general conclusions about preserving surface condition were drawn by Lawson from the many cases that he studied:

(1) The closer the thermal characteristics of materials in a given composite, the less damage there will be to any one material.

(2) The higher the energy density used to cut a given material, the less the damage.

(3) Thinner materials cut better than thicker materials.

(4) Pulsed cutting is usually better than CW.

(5) Nd:YAG lasers gave better cuts than CO_2 lasers on graphite/epoxy laminates (and might be significantly better on inorganic/inorganic composites, which were not studied).

(6) CO_2 lasers (pulsed) are the choice for glass-reinforced composites or for Kevlar.

TABLE 3-18. OBSERVED CUT SURFACE CONDITIONS ON COMPOSITES[17]

Thickness in.	Visual Depth Effects, in. CO_2 Pulsed	Visual Depth Effects, in. CO_2 CW	Visual Depth Effects, in. Nd:YAG Pulsed	Knife Penetration, in. CO_2 Pulsed	Knife Penetration, in. CO_2 CW	Knife Penetration, in. Nd:YAG Pulsed
Graphite/Epoxy						
0.050	ND	NR	ND	0.050	NR	0.010
0.125	0.060	NR	0.05	0.080	NR	0.040
Kevlar						
0.040	NR	0.004	NR	ND	NR	NR
0.093	NR	0.002	NR	0.001	NR	NR
0.120-0.125	0.001	0.010	NR	0.001	0.010	NR
0.4	NR	0.010	NR	NR	ND	NR
Glass Laminate (G7)						
0.100	0.009		NR	0.010		NR
0.250	0.025		0.007	ND		0.004
Glass Laminate (G11)						
0.060	0.005	NR	NR	0.010	NR	NR
0.250	0.02-0.04	ND	NR	0.025	0.030	NR
Glass Laminate (G10)						
0.062	NR	0.010	NR	NR	0.010	NR
0.125	NR	NR	0.020	NR	NR	0.015

NR = not run (no tests carried out with this technique).
ND = no data (test run but observation not available).

3.7 CERAMICS

Lasers have found a niche in the cutting of aluminum oxide. The method used is more akin to drilling than to cutting processes described herein in that a series of holes is formed and the brittle ceramic is caused to fracture along the path. Other ceramics tend to exhibit thermal shock and shatter when exposed to the laser beam. However, partially stabilized zirconia (PSZ) ceramics, with more tolerance to mechanical and thermal shock, are being produced and a few reports of cutting silicon nitride have emerged (Table 3-19).

TABLE 3-19. CUTTING SPEEDS FOR SILICON NITRIDE[3] (Nd:YAG)

Thickness, in.	Speed, ipm 300 W[a]	Speed, ipm 200 W[a]
0.1	2.8	2.0
0.2	1.6	1.2

[a]Derived from the reported model of the machine on which work was accomplished.

REFERENCES

1. Arata, Y., Maruo, H. Miyamoto, I., and Takeuchi, S., "Dynamic Behavior in Laser Gas Cutting of Mild Steel," Trans. Jap. Weld. Res. Inst., 8 (2), 1979, pp. 175-186.

2. Private communication, Spectra-Physics, Inc., Industrial Laser Division, (T. Webber), March 1988.

3. Belforte, D., Industrial Laser Handbook - 1988, PennWell Books, Tulsa, Okla.

4. Hoshina, N., "Toshiba CO_2 Laser System," Toshiba Corporation.

5. Bakowsky, L., "New CO_2 Lasers of 1-4 kW Power with Fast Axial Flow", Proceedings of the 2nd International Conference on Lasers in Manufacturing, Birmingham, U.K., March 26-28, 1985, published by Laser Institute of America, Toledo, Ohio p. 195.

6. "Laser Cutting,"Tooling and Manufacturing Engineer's Handbook, Vol. 4. Society of Manufacturing Engineers, Dearborn, Mich.

7. "Advantages of Laser Cutting and Welding of Motor and Generator Laminations," Lumonics, Laserdyne Products.

8. Powell, J., Cut Edge Quality Improvement by Laser Pulsing, IFS (Publications) Ltd., U.K., March 1985.

9. Ruselowski, J. M. "Laser Selection for Drilling," SME Technical Report, May 20-22, 1986.

10. Weick, J. M., "Laser Cutting of Sheet Metal in Modern Manufacturing," Proceedings of the 2nd International Conference on Lasers in Manufacturing, Birmingham, U.K., March 26-28, 1985; published by Laser Institute of America, Toledo, Ohio.

11. Skutley, K. F. "Multi-Axis Laser Cutting," Manufacturing Technology Division, Air Force Materials Laboratory, Wright-Patterson Air Force Base, Ohio 45433, AD-B014622, September 1975.

12. Ruselowski, J. M., "Laser Selection for Cutting," Proceedings of Conference on Lasers in Manufacturing: S-P-O-T '87, Los Angeles, Calif., March 24-26, 1987.

13. "Laser Cutting of Al 7075 Sheets," Proceedings of the 2nd International Conference on Lasers in Manufacturing, Birmingham, U.K., March 26-28, 1985; published by Laser Institute of America, Toledo, Ohio.

14. Marx, W., "Manufacturing Methods for Multi-Axis Laser Cutting," Grumman Aerospace Corporation, Bethpage, N.Y. 11714, ADB012426, November 1975.

REFERENCES (contd.)

15. Vanderwert, T., "Machining Plastics...with Lasers," Manuf. Eng., November 1983, p. 55.

16. "Section 9 - Machining, Assembly and Assembly Forms - Laser Cutting," in Composites Handbook of Engineered Materials, Vol. 1, ASM International, Metals Park, Ohio, p. 676 ff.

17. Lawson, W. E., "Laser Cutting of Composites," Proceedings of Conference on Composites in Manufacturing, January 5, 1986, published by Society of Manufacturing Engineers, Dearborn, Mich.

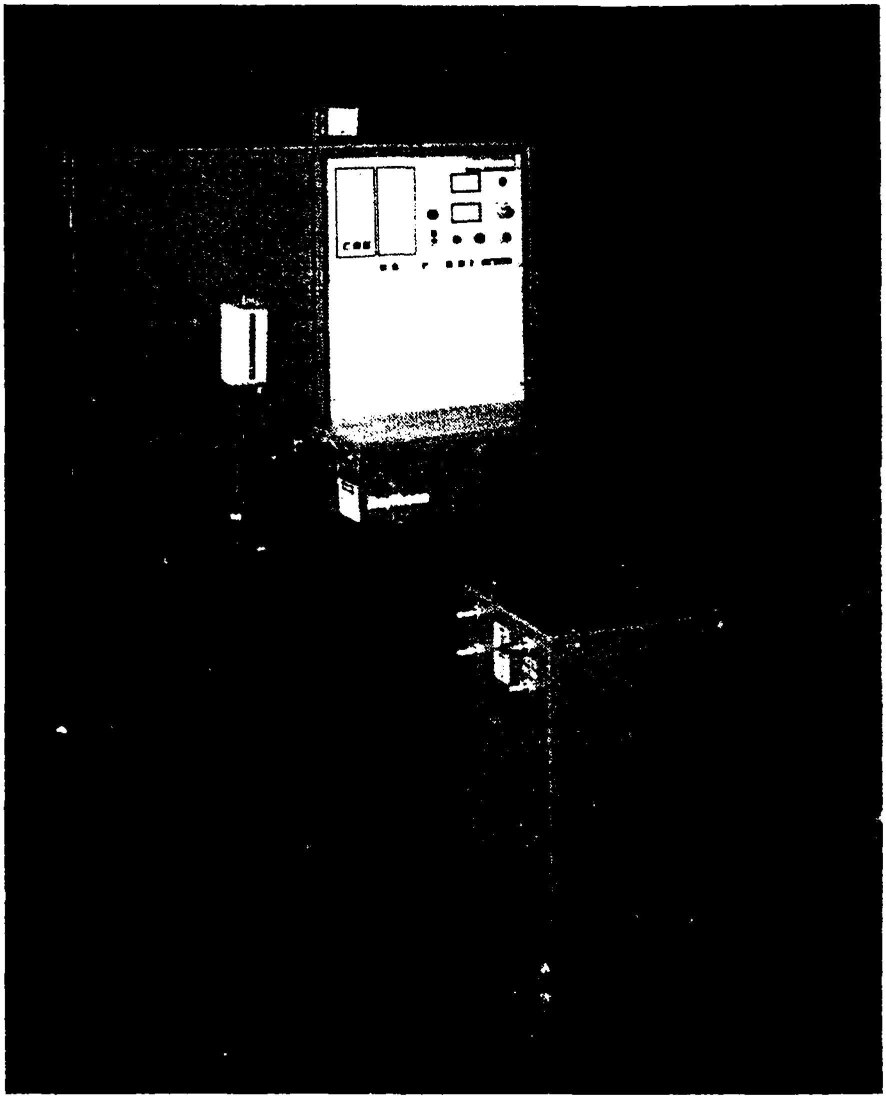
4. LASER BEAM SOURCES

Section 3 discussed the state-of-the-art for various cutting processes. The next two sections describe systems that are available to meet process expectations. A laser system embodies two subsystems: The first is the laser itself, which is directly responsible for the process/material interaction regardless of the size or shape of the workpiece. The second component is the manipulator, which moves the process relative to the workpiece for any specified laser. Section 4 deals with the laser beam source, and Section 5 covers manipulators.

4.1 LASERS FOR CUTTING

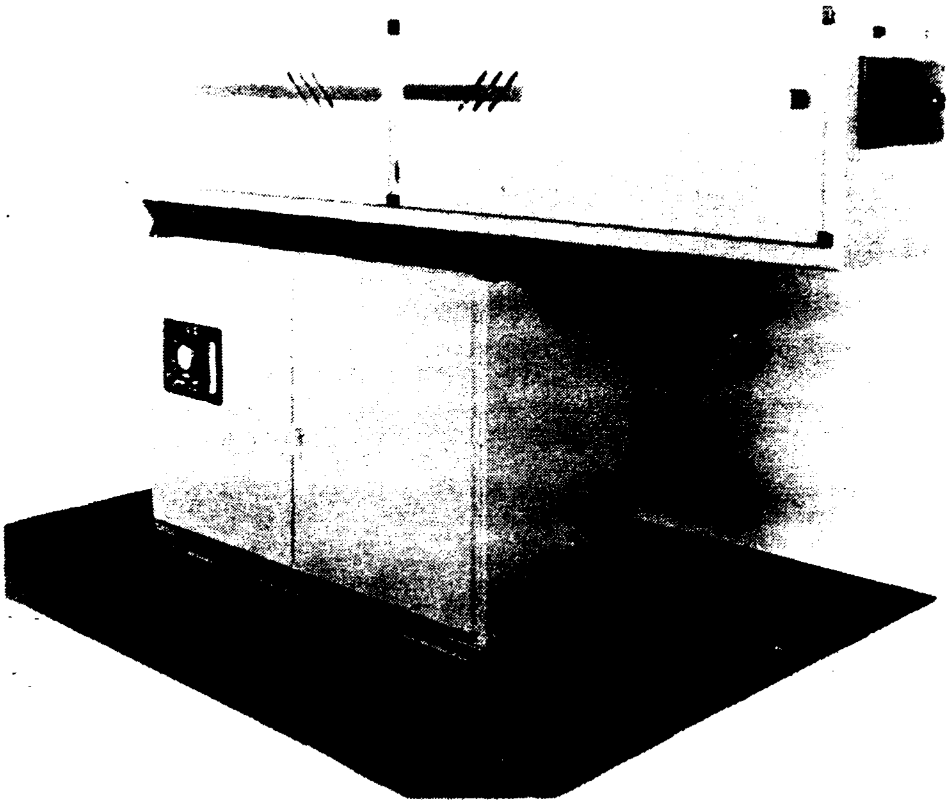
Manufacturers in the material working industry require at least several hundred watts of power for cost-effective cutting. This requirement, which often extends to more than a kilowatt, has led to the domination of laser cutting by two technologies: neodymium:yttrium-aluminum-garnet (Nd:YAG) solid-state technology (Figure 4-1), and carbon dioxide (CO_2) gas technology (Figure 4-2). Of the two, CO_2 technology is most frequently encountered. CO_2 is particularly effective on plastics and other organic materials. However, Nd:YAG was often limited to such technically demanding applications as the cutting of thick high-temperature[1] alloys. More recently, the Nd:YAG technology has attracted attention in the material cutting industry because it is adaptable to quartz fiber optic beam delivery systems while CO_2 technology is not. Additionally, there is some evidence that Nd:YAG has an advantage in the cutting of composites (see Section 3). Commercially available lasers from both technologies are listed in buying guides that are published annually by several organizations (e.g., Reference 2). Both types of lasers will be discussed here.

Excimer laser technology deserves brief mention at this point because it offers a reportedly nonthermal approach to the cutting of delicate plastics.[3] For example, an excimer laser was reported[4] to have cut a 0.012 in. diameter hole in a polyimide sheet with no visible evidence of thermal damage.[4] At present, emphasis seems to be on the micro manufacturing aspects



Source: Raytheon

Figure 4-1. Nd:YAG laser head.



Source: Coherent General

Figure 4-2. CO_2 laser head (slow-flow configuration).

of the electronics industry[3] and the technology has not been reduced to industrial standards, according to comments written as recently as 1986.[5] By 1988 at least one product listing[2] alluded to the "relative youth" of the technology as a hindrance to its listing and ranking, suggesting that it cannot yet be considered as part of the industrial state-of-the-art.

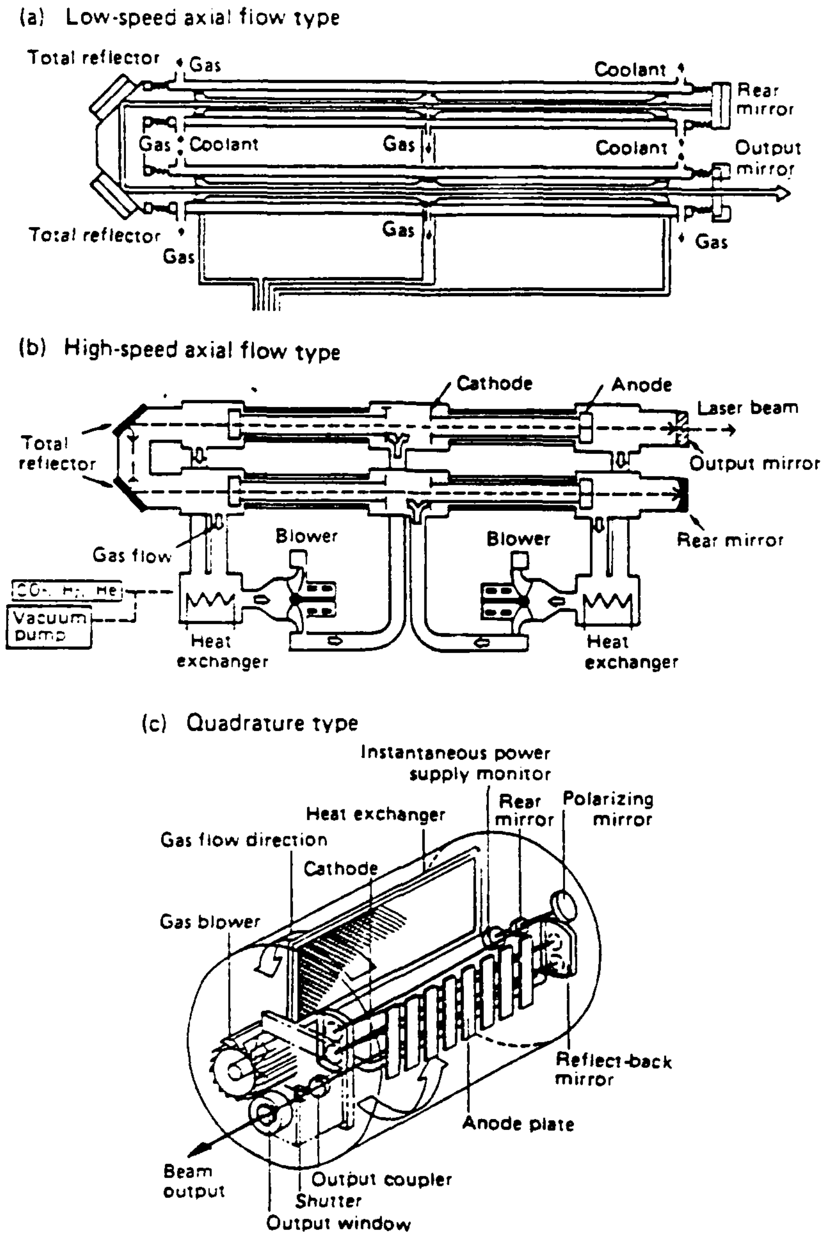
The following paragraphs describe the two major types of lasers for cutting material--the CO_2 and the Nd:YAG. They are vastly different in their physical configuration. Recent developments have greatly increased power/size ratios and have opened up new possibilities for system design.

4.1.1 CO_2 Configurations

The CO_2 laser operates by producing a discharge in a mixture of gases, one of which is CO_2. The concept was introduced in 1964. The output is an invisible beam of 10.6 μm, far-infrared radiation that can only be transmitted effectively by a few semiconductor materials and potassium (or sodium) chloride crystals. Helium (He) and nitrogen (N_2) are mixed with the carbon dioxide (CO_2) lasant. The technology, therefore, is based on enclosing and moving gas mixtures at low pressures, removing waste heat from the 10-20% efficient process, and establishing an electric discharge in the gas medium without causing arcing within the region where the beam is formed.

Industry's approach to this technology has led to several distinct categories of CO_2 laser, three of which are powerful enough to be attractive for commercial manufacturing operations (Figure 4-3). The thrust has been to provide high power levels without unduly sacrificing beam quality. The CO_2 laser categories that are most prominent in material working operations are: slow axial flow, fast axial flow, and fast transverse flow.

(a) Slow Axial Flow. This category of CO_2 laser is the simplest of the three and consists of a long, small-diameter glass tube with an electrode at each end. Air is removed from the tube, which is then backfilled to a low pressure with a mixture of CO_2, helium, and nitrogen. A direct high-voltage current flows between the electrodes in the direction of the axis of the tube. The electrical discharge excites the CO_2 and N_2 atoms. Helium helps to remove the energy remaining in the CO_2 molecules after lasing. A mirror system at both ends of the tube is used to collimate the radiation resulting from the discharge. Waste heat is conducted through the walls of the tube.



Source: Amada/Metalwork. Eng. Mark.

Figure 4-3. CO_2 laser configurations.

Each meter of discharge can produce about 50 W of laser power.[6] During discharge the gas is heated and there is some gas decomposition. The gas is slowly removed from the tube by a small vacuum pump to permit cool gas to enter and to remove the decomposition products, hence the term slow flow. Clearly, the number of meters of discharge length required to achieve power levels necessary for commercial cutting results in a very large laser. However, the beam quality is very high and pulsing is readily accomplished through the use of a separate power supply. The slow-flow technology is most frequently encountered at power levels up to 500 W, with one 800 W and 1000 W listed as commercially available.[2]

(b) Fast Axial Flow. More power can be gained from each meter of discharge if the gas is rapidly removed from the active region to a separate heat exchanger where the heat can be removed. Gas must be changed often to keep it from heating too much. Power is proportional to flow, rather than length.[7] Thus the design emphasis is on the movement of gas in this class of CO_2 lasers. Flow rates of 1 m/s have been reported.[8]

Since about 1985 there have been two methods of exciting the fast-axial-flow lasers.

- Longitudinal (dc) discharge similar to slow-flow lasers but requiring some induced gas turbulence to reduce discontinuities in the discharge. Such systems constituted the original approach to fast-flow excitation technology and involve very high voltage (10-20 kV).[8] Output can be 1000 W/m for these fast-flow lasers.

- RF discharge is applied transverse to the tube axis along its length. The RF excitation technique is reported to reduce voltages in the laser and increase electric power density 3 or more times over dc levels. Reduced voltages and higher electrical input densities permit better discharge stability than longitudinal discharge lasers. Additionally, gas contamination caused by erosion of the exposed electrodes during dc discharge is eliminated because the RF electrodes are external to the tube.[8]

Beam quality and pointing stability are very similar to the slow-flow technology. The fast-flow technology dominates the 500-3000 W power range. A few examples are listed below 500 W and up to 7000 W.[2]

The need for rapid gas flow through the restriction of the tubular configuration leads to the need for positive displacement blowers capable of

operating at low pressures and high pressure differentials[9] without leakage through the seals. Placement of the motor inside the shell of the blowers is being introduced to meet this performance requirement.

(c) Fast Transverse Flow. In order to achieve higher power, designers have replaced axial flow through tubes with a transverse flow through a short, wide, boxlike channel. The gas traverses the width of the box while the discharge and/or the beam operates transverse to the gas flow. Only fans are needed in such a situation,[9] and concern for the reliability of high-pressure pumps is eliminated. However, the electrical discharge must be both sustained and stabilized. Stabilization ensures that the electric current passes through the entire volume between electrodes rather than collapsing into a lightning bolt-like discharge between one point on an electrode and a point on the opposite electrode.[6] There are two methods for accomplishing stabilization in industrial lasers. One method incorporates ballasted parallel electrical input channels using resistance, inductance, or capacitance to counteract sudden high current flow through any one channel. The other uses a simpler nonchanneled electrode covered with a suitable dielectric. There does not appear to be any advantage of one method over the other.[9]

The added complexity of the transverse flow concept does, however, result in a very compact unit. Output levels of more than 2000 W/m have been reported for transverse flow units.[10] Transverse units tend to be most prevalent in the power range of 3-25 kW.[2] Most transverse-flow units produce a beam of lower quality than do the axial-flow systems. Additionally, pointing stability should be reviewed when considering complex beam delivery systems.

4.1.2 Nd:YAG Configurations

The Nd:YAG laser produces its characteristic radiation when a pencil-like crystal (rod) of yttrium-aluminum-garnet doped with the neodymium ion (Nd^{+++}) is excited by the light from an arc or flash lamp. The Nd^{+++} is the lasant. The output is a near-visible beam of 1.06 μm near-infrared radiation that can be transmitted by glass optics. The wavelength is not readily absorbed in many plastics but is readily absorbed by metals, compared to CO_2 beams. The Nd:YAG laser head is much more compact than equivalent CO_2 lasers, based as it is on one or more 3/8 in. diameter, 6 in. long emitting elements. The technology has had to address power limitations and a rather poor beam quality but

has achieved high levels of compactness and ruggedness. This approach has led to three types[11] of industrial Nd:YAG lasers while a fourth type is now being considered for industrial use.

(a) Single-Cavity Resonators. The resonator refers to the arrangement of light generation elements located between the mirrors. A cavity is that portion of the resonator which supports one Nd:YAG crystal and one or more lamps. A typical resonator/cavity arrangement is shown in Figure 4-4. Most cutting has been accomplished with this type of configuration. Beam quality may not be as good as it is with, for example, slow-flow CO_2 lasers, but the Nd:YAG wavelength is more easily absorbed by metals, resulting in the commercially accepted process performance listed in Section 3.

(b) Single-Cavity, Optically Modified Resonators. Figure 4-5 shows an Nd:YAG configuration that has been optically modified to operate with improved beam quality. In either Figure 4-4 or 4-5, power output is limited to an emission level not exceeding 600 W/in.[3] Optical modification selects only a portion of the normal output so that optically modified lasers are inherently low power (10-20% of their unmodified counterparts). Loss of power is somewhat offset by improved beam quality. Improved beam quality permits increased spot intensity. This type of laser is used for the percussion drilling of small holes but can also produce high-quality cuts (e.g., when used to trepan larger holes).

(c) Multiple-Cavity Oscillator Amplifier. Figure 4-6 shows a resonator that has two crystals, each with its cavity elements (lamps, reflective surfaces, etc.) and illustrates the third type of Nd:YAG laser. These multiple (2 or 3) cavity arrangements have extended maximum available power levels from 400-500 W to 1200 W (CW). Product performance parameters relating to beam quality[2] are not greatly different from those listed for the single-cavity lasers. Large-diameter (0.01 in. and greater) holes of moderate quality are produced by these lasers,[11] but they can penetrate 1 in. thick plate. Lasers in the 1200 W (CW) category have only become a part of the state-of-the-art since the mid 1980s and extend the power range of the solid state toward that of the CO_2 technology.

(d) "Slab" Lasers. Figure 4-7 illustrates a Total-Internal-Reflection, Face-Pumped Laser (TIR-FPL) or "slab" laser, which represents an advanced approach to the goal of high power and good optical quality in a compact

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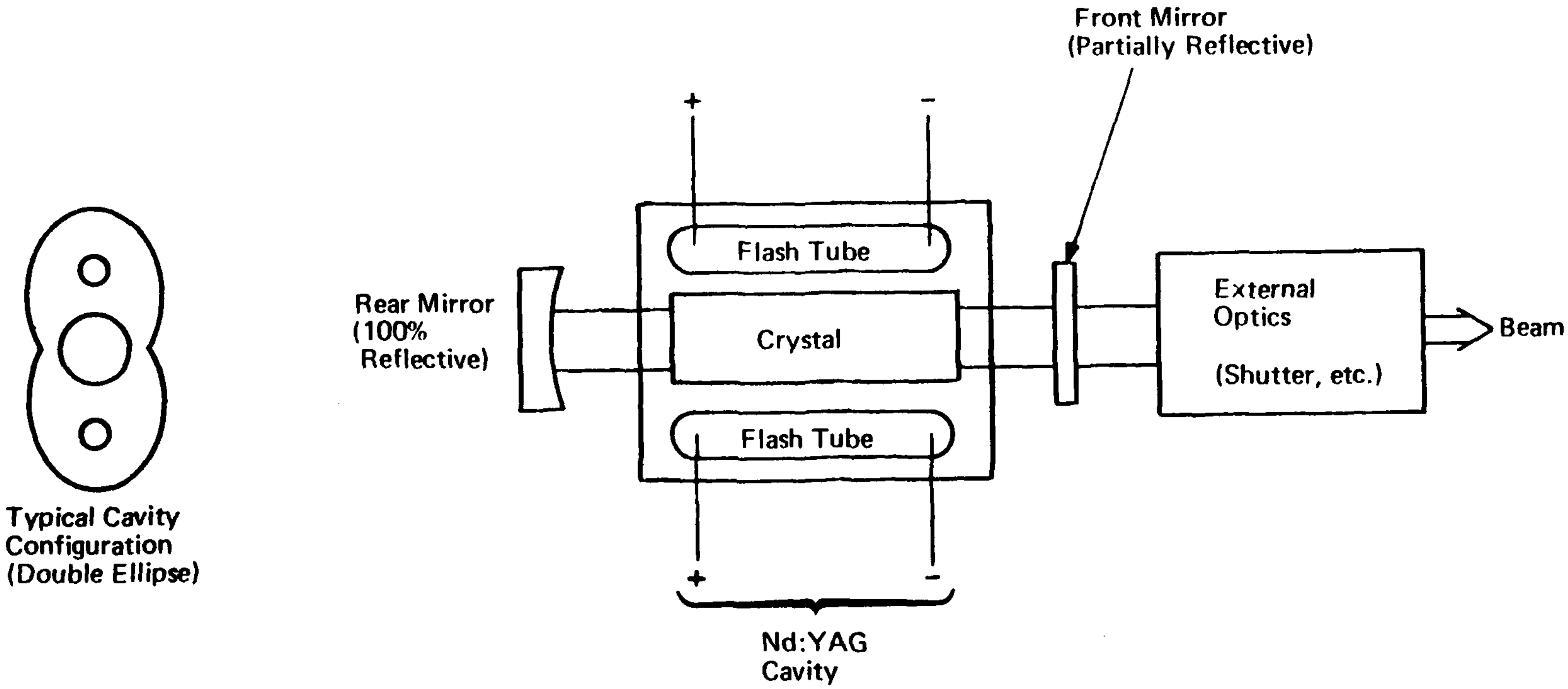

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Figure 4-4. Typical arrangement of Nd:YAG resonator.

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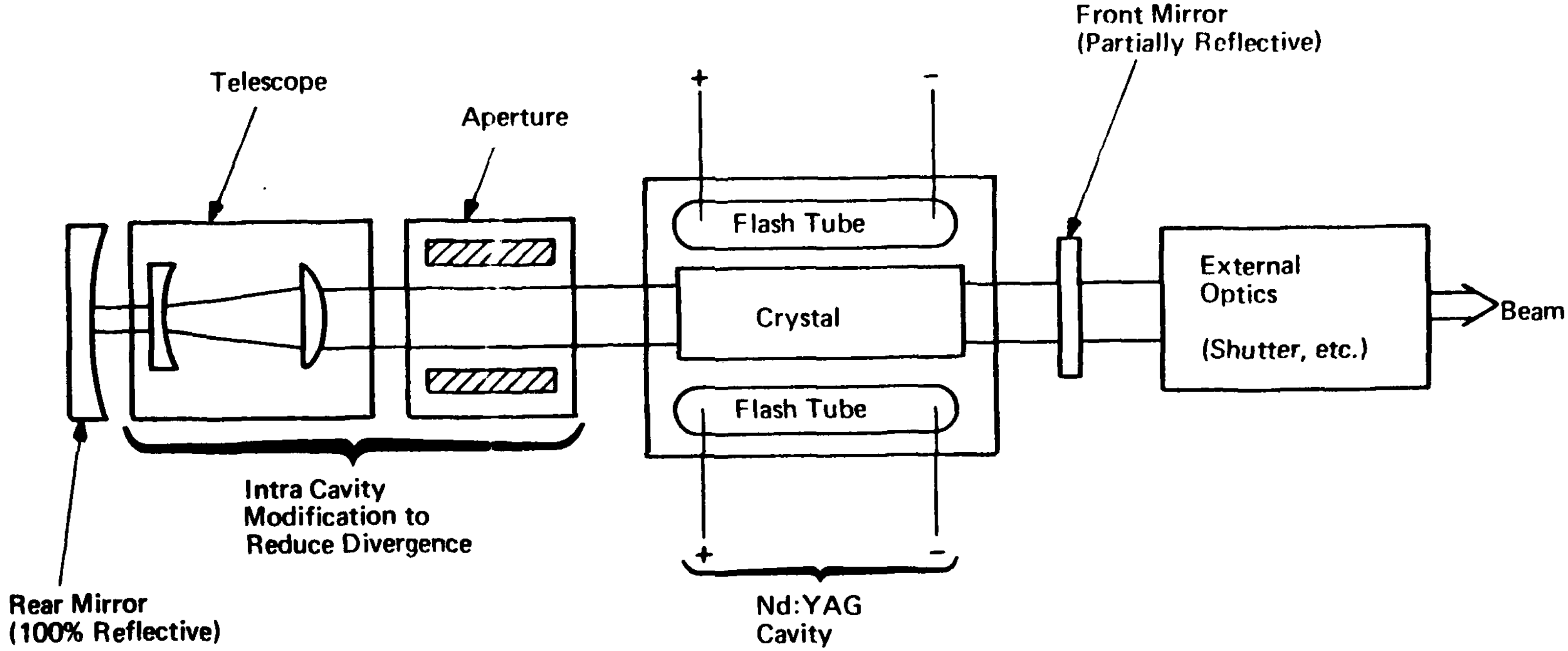

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Figure 4-5. Optically modified single cavity Nd:YAG resonator.

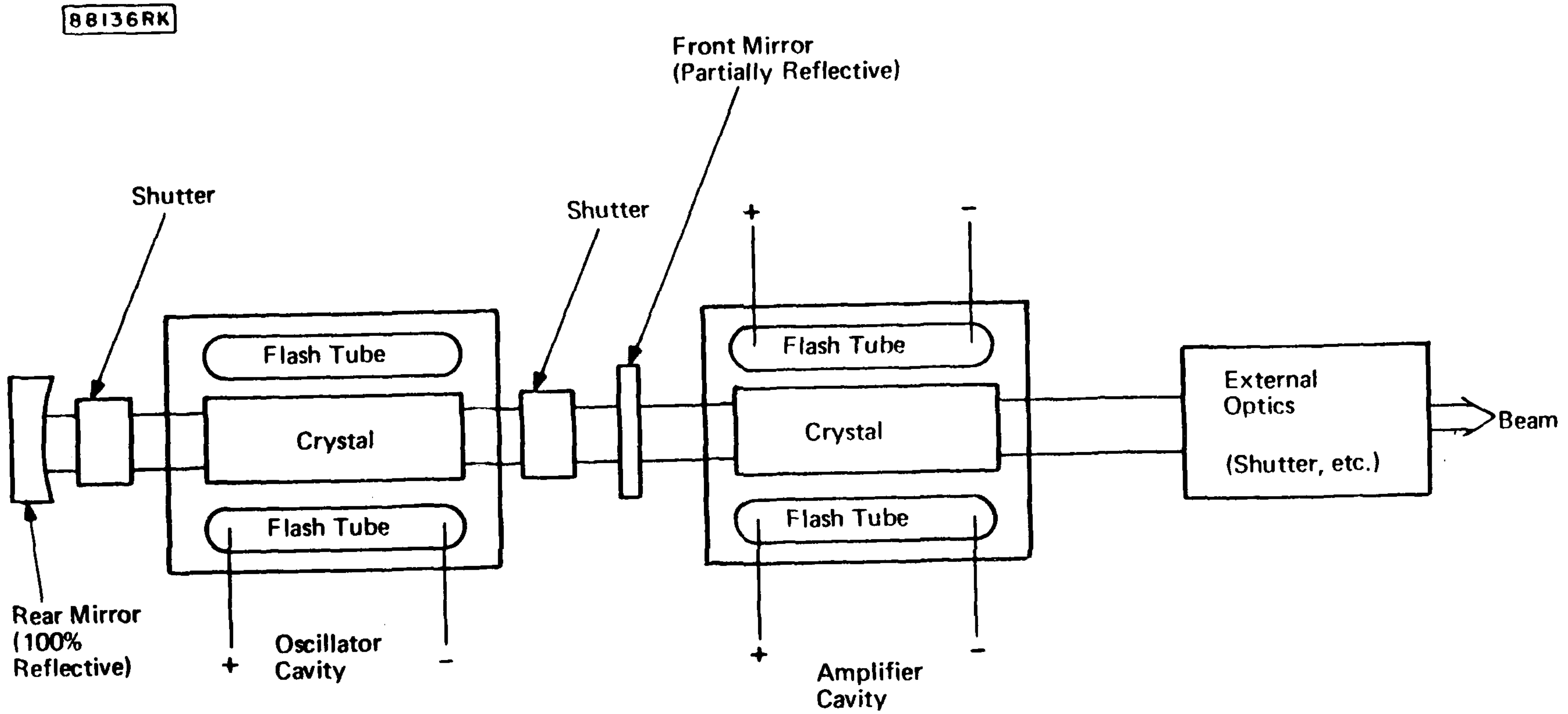

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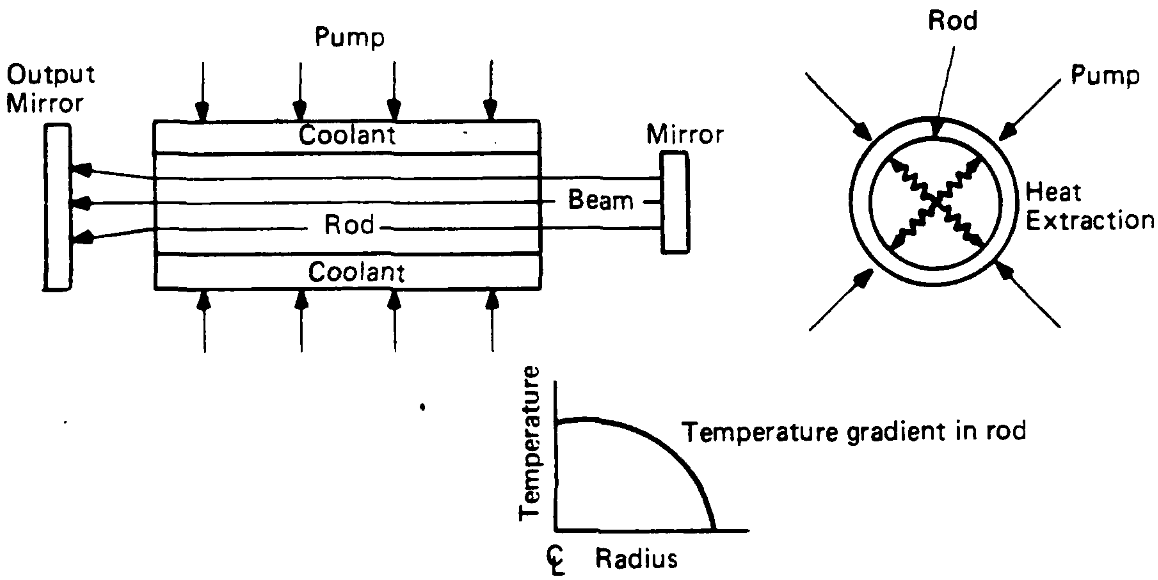
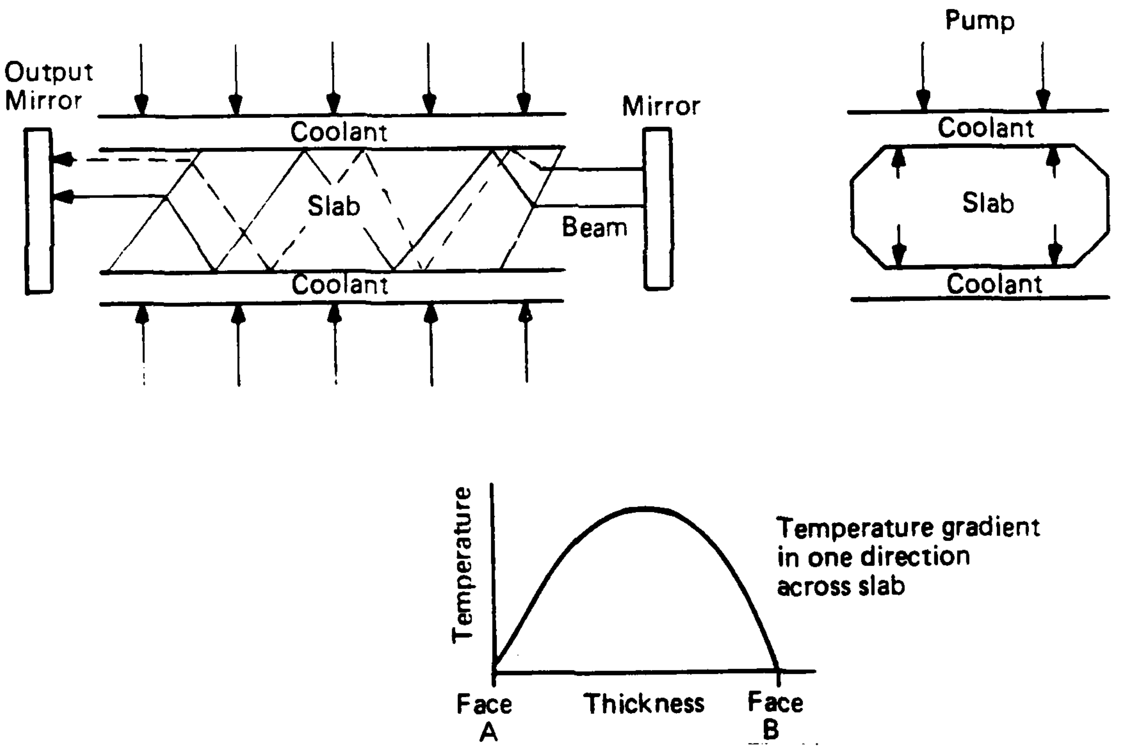
Figure 4-6. Dual cavity Nd:YAG oscillator amplifier.



(a) Conventional rod laser



(b) Slab--total internal radiation laser (face-pumped)

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Source: *IITRI*

Figure 4-7. Slab vs. conventional laser.

solid-state laser head. The resonator is arranged so that the beam follows a zigzag path through the 1 x 3/4 x 8 in. slab cut from a larger crystal of Nd^{+++} doped YAG. The beam passes through all parts of the cooling gradients and thus tends to average out the thermal distortion that characterizes the conventional cylindrical rod shape. Slab lasers are reportedly undergoing industrial trials at the 600 W average power level.[12] Test results suggest good beam quality at power levels great enough to increase the penetration range for the Nd:YAG technology from 3/4 in. to 2 in. in steel.[13]

4.2 POWER OUTPUT

The power that is emitted by the laser is applied to the cutting process in one of two forms:

- Continuous: Laser systems have reached a level of stability where they can deliver a set amount of power without interruption. A typical CO_2 laser, for example, can now be expected to produce a continuous output (often called a CW--continuous wave--output) for 24 h with a variance no greater than ±2% of the set power.[4]
- Pulsed: Originally considered a means for enhancing the penetrating capacity of a laser by delivering power in the form of a spike-like discharge, pulsing has come to be recognized as an essential tool for the control of overheating during the cutting of complex details (e.g., trepanned holes, sharp outside corners[14]). Nd:YAG lasers have always operated in the pulsed mode as have small CO_2 lasers. However, within the past few years recognition of the importance of pulsing has caused it to be introduced into commercial lasers at progressively greater power levels until today pulsing is available on 6000 W lasers.[2]

4.2.1 Continuous Wave (CW) Power Output

The CW power of a laser can be easily determined by reviewing commonly available lists of equipment that state the maximum number of watts sustainable for a significant period of time (e.g., several hours).[2]

CO_2 Lasers. Currently CO_2 lasers with CW power output capabilities of 10,000 and 25,000 W are listed,[2] and several such lasers are in operation in limited production applications. A closer approximation to the commercial state-of-the-art would be a 5000-6000 W maximum based on several automotive welding applications. All of these very powerful lasers exhibit multimode or

"near single mode" operation. For single-mode CO_2 lasers that would permit efficient cutting operations present listings[2] suggest that 3000 W is the upper limit.

Nd:YAG Lasers. CW is not normally used for cutting with Nd:YAG lasers; however, CW power is available. Since 1987, Nd:YAG lasers with a CW power level greater than 600 W have been listed. Recently the maximum available power level has been raised to 1200 W, and a 1000 W unit is specifically described as suitable for a "welding/cutting" system.[2]

4.2.2 Pulsed Power

Pulsed power can be considered a means for controlling the delivery of power when cutting complex shapes. Evaluation plus power capability is difficult using currently compiled equipment parameters. Average power, the peak power in each pulse, or the maximum number of joules per pulse must be determined in order to make comparisons.

Pulsing can also be considered as enhancing the delivered power for short periods. Spiked pulses assist in overcoming initial reflectance and reducing dross in some materials.

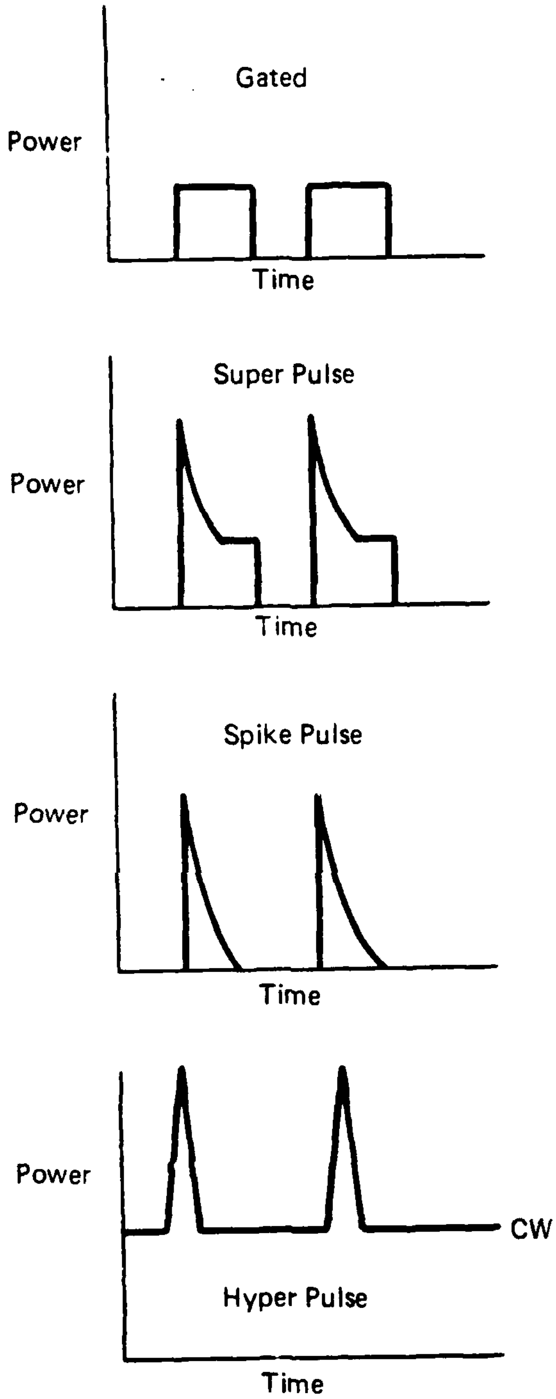
CO_2 Lasers: There are four[15] regimes of pulsed operation available for CO_2 lasers (Figure 4-8):

(1) Gated Pulses: On/off programming of the power or mechanical chopping of the CW mode with no spikes. This pulsing regime is for power control in complex cuts.

(2) Super Pulse (or enhanced pulse): Spikes of about 100 μs duration added to the leading edge of a gated pulse. Maximum power reached by spikes is 3-4 times greater than the gated pulse for capacitive pulse power supplies[4] and may be increased to 4-6 times greater by changing the proportions of the various components in the gas mixture. Spikes that are 10 times greater than average power are reported for RF or inductively pulsed systems.[4] This pulsing regime is used to break down reflection on materials such as copper or gold.

(3) Spike Pulse: Same as 2 above but not added to a gated pulse. Spikes are used to assure a round hole when drilling very fast moving work such as reels of paper tape.

(4) Hyper Pulse: Adds spikes on top of continuous (CW) power. Appears to utilize the spike to overcome reflectance while using the continuous power input to maintain the fluidity of dross until it can be blown from the cut. The technique has been effective in producing dross free aluminum cuts.



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Source: IITRI

Figure 4-8. Pulse configurations for CO_2 lasers.

CO_2 systems can be pulsed at repetition rates of several thousand hertz.

<u>Nd:YAG Lasers</u>. Nd:YAG lasers are limited to lower repetition rates than CO_2 systems. Each pulse consists of a series of naturally occurring spikes that tend to smooth out towards the end of each pulse[8] (Figure 4-9). The relationship between average power and the peak spike power is influenced by the type of supply used to power the flash lamps. There are two types of supply: (1) capacitor--produces maximum peak power; (2) solid state--controls each pulse but produces a slightly lower peak power.[16]

4.3 EXTERNAL OPTICS

Once a given configuration of laser head has emitted a beam of radiation, that radiation must be brought to the work surface and focused using external optics (to differentiate them from the internal optics that form the resonator inside the cavity).

In the area of optics, the state-of-the-art involves several differences between CO_2 and Nd:YAG technologies and has recently involved new and highly flexible means of delivering the beam.

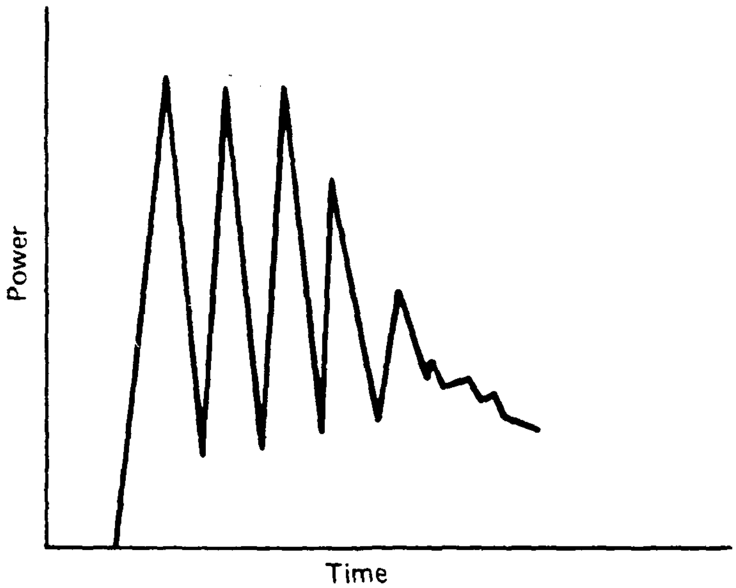
4.3.1 Optics for Nd:YAG Lasers

The Nd:YAG laser transmission optics are made from quartz and coated with materials that modify the Fresnel reflection coefficient and thus minimize reflection. The 1.06 μm near-infrared wavelength of the Nd:YAG is readily transmitted through such materials.

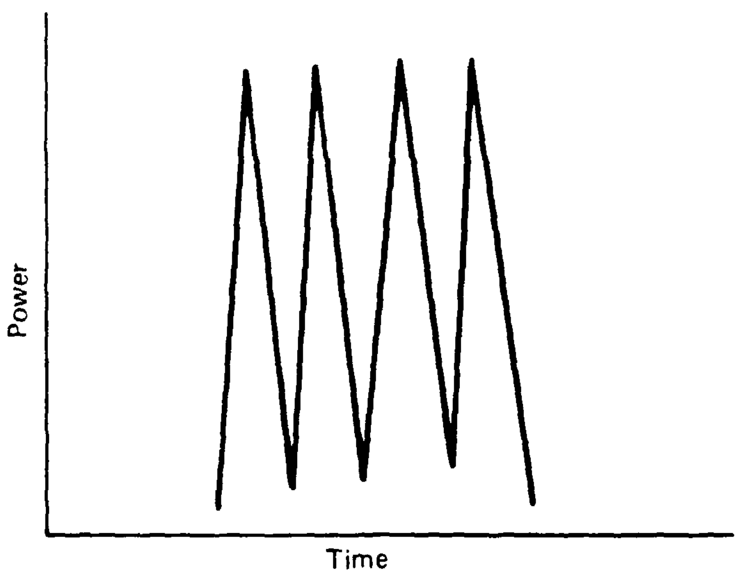
Quartz optics for Nd:YAG lasers cost less than the special optics for CO_2 lasers. One operating-cost analysis estimates that the cost of procuring and maintaining optics for an Nd:YAG is one half that of CO_2 lasers.[11] The compatibility of the Nd:YAG beam with low-cost quartz also permits the use of expendable protective slides where the process tends to eject smoke and debris up into the cutting nozzle (e.g., when drilling through to start a cut on the surface of a plate instead of at the edge).

<u>Mirrors</u>. The Nd:YAG wavelength is absorbed by polished metal surfaces which makes difficult the use of mirrors of metals other than gold or silver.

<u>Fiber Optics</u>. Nd:YAG fiber optic technology has progressed to commercial power levels above 100 W over 25 m. Usage to 400 W has been cited, but results



(a) Nd:YAG pulse



(b) Nd:glass pulse

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Source: IITRI

Figure 4-9. Pulse configurations for Nd:YAG and Nd:glass lasers.

under extended operation have not been reported.[4] Losses of 15% overall are reasonable to expect.[4] Nd:YAG fibers have been developed from fused silica (quartz), which readily transmits the characteristic Nd:YAG radiation.

4.3.2 Optics for CO_2 Lasers

The 10.6 μm far-infrared beam is only transmitted in industrial processes by the following materials:

- **Zinc Selenide**: This semiconductor material also permits some transmission of visible light so that it can be used in systems that provide television or a safe coaxial system system for viewing the spot impingement area. Properly coated, this material exhibits acceptable resistance to damage by smoke and debris.
- **Gallium Arsenide**: Although opaque to visible light, gallium arsenide can transmit the CO_2 wavelength and withstand exposure to the atmosphere including smoke and debris. Gallium arsenide is slightly more sensitive than zinc selenide to the power density being transmitted, and is often chosen for optics in systems with power levels below 1000 W.[15]
- **Potassium Chloride**: This material is very sensitive to change because of small amounts of moisture in the air and must be protected under ambient conditions. It exhibits good transmission of CO_2 wavelengths. Sodium chloride can also be used but is even more sensitive to moisture in air.

The complexity and cost of the above transmissive materials preclude their use for low-cost protective elements in CO_2 cutting heads.

Transmission is not perfect in any optical component, and service life suffers as power increases. This becomes a significant consideration for CO_2 transmission optics as laser power approaches the multikilowatt (3-6 kW) level. Differentially pumped openings in the laser cavity may be used in place of solid optics to bring the beam out of the laser provided that gas losses through the openings are not considered excessive.

Metal Mirrors. Mirrors are beginning to be accepted as focusing elements in CO_2 systems. Mirrors are said to provide the same optical spot size as planoconvex lenses.[17] In addition,[18] metal optics:

- Avoid variance of focal point location that occurs as the lens heats and cools during operation.
- Can be wiped clean without damaging optical quality.

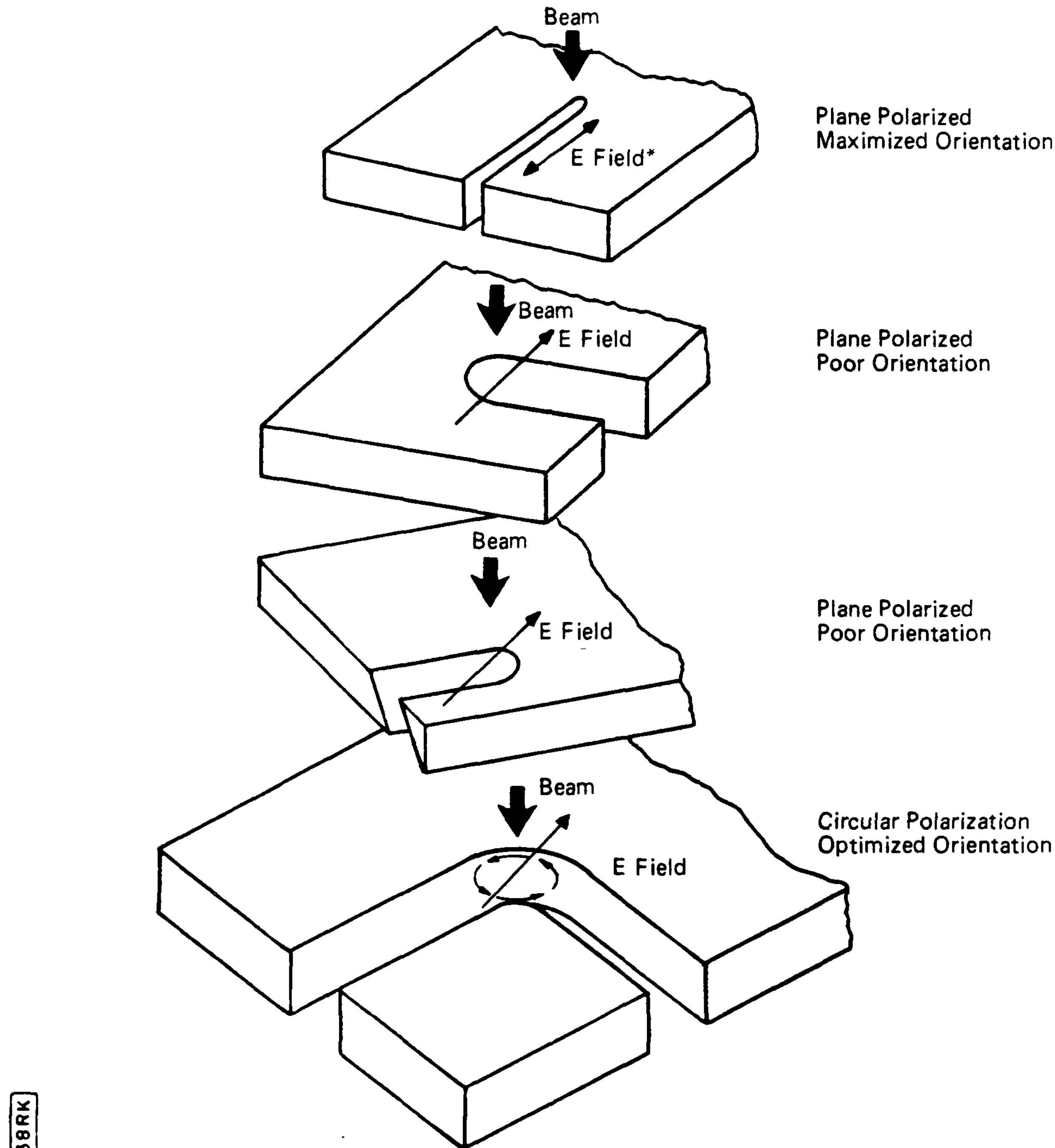
The latter advantage is most readily available on molybdenum mirrors. Copper or aluminum mirrors are often used because they are easily manufactured and provide a stable focal point location, but some precautions must be taken in cleaning them. Mirror losses are typically estimated to be 2% or less per surface. Mirror surfaces constantly change under room conditions so that some control of the environment around mirrors and/or periodic cleaning is required. A common approach to such control is to shroud the beam and slightly pressurize the shroud with dry nitrogen.

Fiber Optics. The characteristic CO_2 radiation is not transmitted by quartz so that current fiber optic technology is not appropriate to CO_2 lasers. Fibers must be made from dielectric materials such as ZnSe, and AgI which can transmit the 10.6 μm wavelength that characterizes CO_2 technology. Development in Japan of such fibers has been reported, but the transmission is limited to about 5 W per fiber.[19]

Circular Polarization Optics. CO_2 beam paths within the cavity are frequently folded in order to obtain as much beam path length as possible within a given laser head. Folding the beam results in a linearly polarized output.

Cutting performance can vary by 50%, depending upon the relative orientation of the cut path and the polarization direction of the beam.[4] Figure 4-10 illustrates the effect of polarization direction on cut geometry. Stable linear polarization would be ideal if its direction could be optimized with respect to the cut path and the cut direction never varied, as in the case of sheet metal slitting. However, most cuts are multidirectional. Circular polarization is used for multidirectional cuts.

Circular polarization has the same effect during cutting as no polarization[4] and is introduced into the beam by external optics supplied with birefringent coatings. Birefringent materials have a high index of refraction in one direction and a low index of refraction in the perpendicular direction. These materials serve (when properly oriented) to retard one of the orthogonal components of a plane polarized wave. Delaying one component by one quarter wave causes the vector sum of the polarized wave to describe a helix with a period equal to the wavelength of light. When the light is deposited on the work surface, the helical vector path is projected as circular polarization.



* E field arrows refer to the electric field component of an electromagnetic wave. The electric field component defines the direction of plane polarization within the beam.

Figure 4-10. Effect of polarization direction on cut geometry.

Figure 4-11 is a schematic of a circular polarizer. Such devices are sometimes called "enhanced cutting accessories."[4]

High-power Nd:YAG lasers cannot be polarized and still retain their efficiency because the crystal itself becomes birefringent, thereby destroying the effectiveness of any polarizing element.

4.4 AUXILIARY GAS NOZZLES

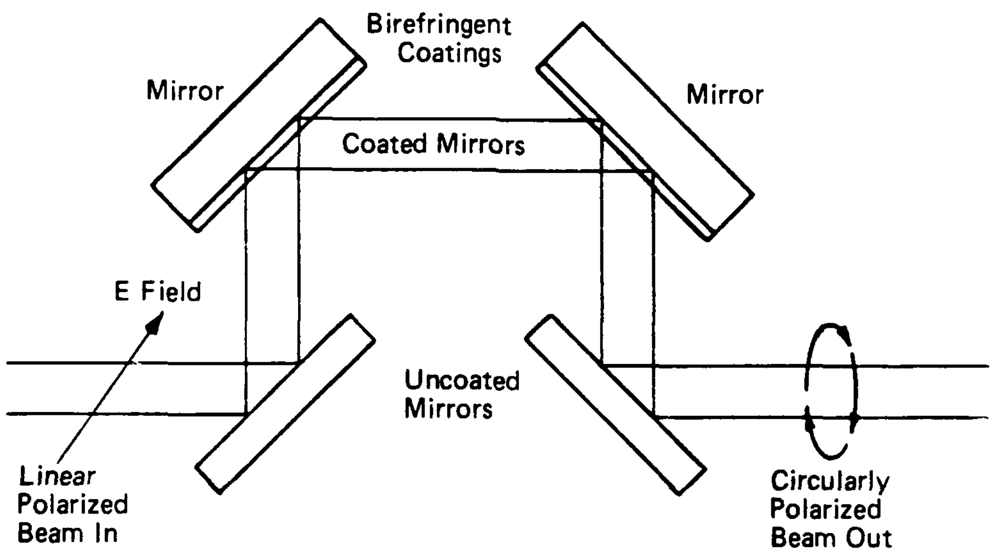
The gas that is directed into the cut coincident with the laser beam is often called auxiliary gas, although such gas is actually an integral part of most cutting operations. The role of gas ranges from active to passive. In its passive role, gas serves to protect the cutting optics from debris and smoke or an inert gas cover may be used to minimize oxidation in the cut. Oxidizing auxiliary gases play an active role in cutting by providing a significant portion of the process heat through reaction with the material being cut. The use of a coaxial jet of oxygen or air as part of the cutting process for carbon steel is an example. In recent years, attempts have been made to increase the process efficiency through improved use of the gas stream.[20]

Originally, most cuts were made with relatively low gas pressures. Several attempts to improve cutting performance by increasing gas pressure have led to the observation that there is promise over small ranges of pressure but that process repeatability suffered as pressure increases were extended.[20] Recent investigations have suggested the reason and resulted in an approach to raising present pressure limits without sacrificing speed, quality, or reproducibility.[20]

There now appear to be two distinct regimes in nozzle/cut technology. These regimes involve cutting with a gas stream velocity that is either (1) subsonic or (2) supersonic. Conventional gas nozzles, with throats that are circular in cross section, exhibit supersonic velocities at pressures of 2-4 bars and above.

4.4.1 <u>Cutting with Subsonic Gas Flows</u>

Subsonic gas streams transfer the pressure (P_N) of the gas in the reservoir that is formed by the lens and nozzle body (Figure 4-12) more or less directly onto the work. Cutting effectiveness is a function of pressure on the work (P_C). Pressure (P_C) drops off only about 15% as the nozzle-work



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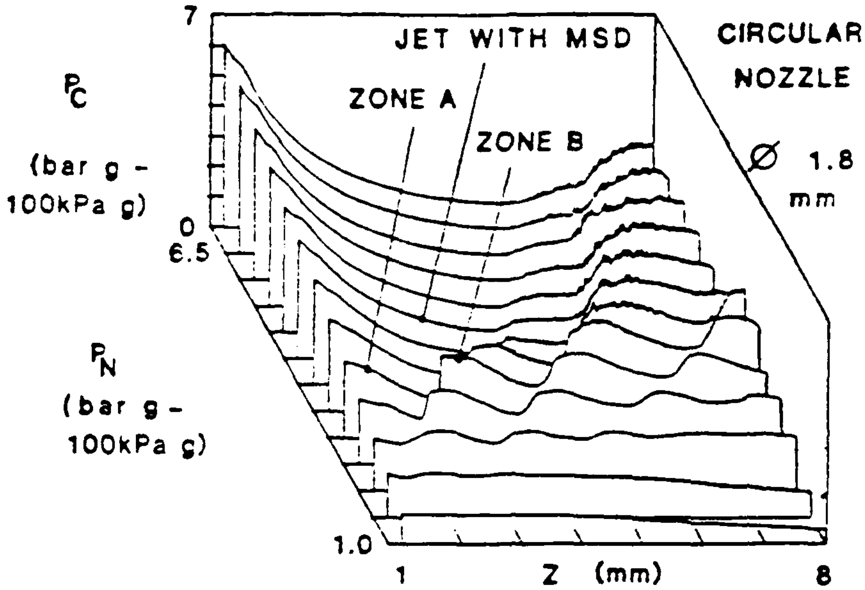
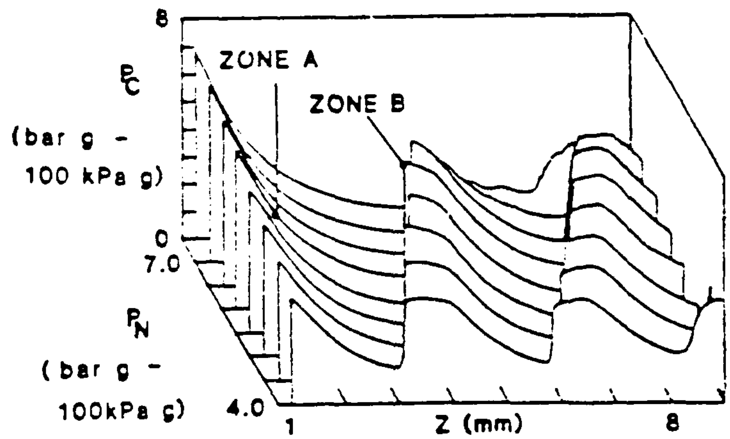
Source: IITRI

Figure 4-11. Schematic of a circular polarizer.



(a) Variation with circular nozzle



(b) Variation with star-lobed nozzle

Z = distance from nozzle tip
P_C = pressure at work surface
P_N = pressure in nozzle reservoir

Source: Culham Laboratories

Figure 4-12. Cutting pressure behavior.

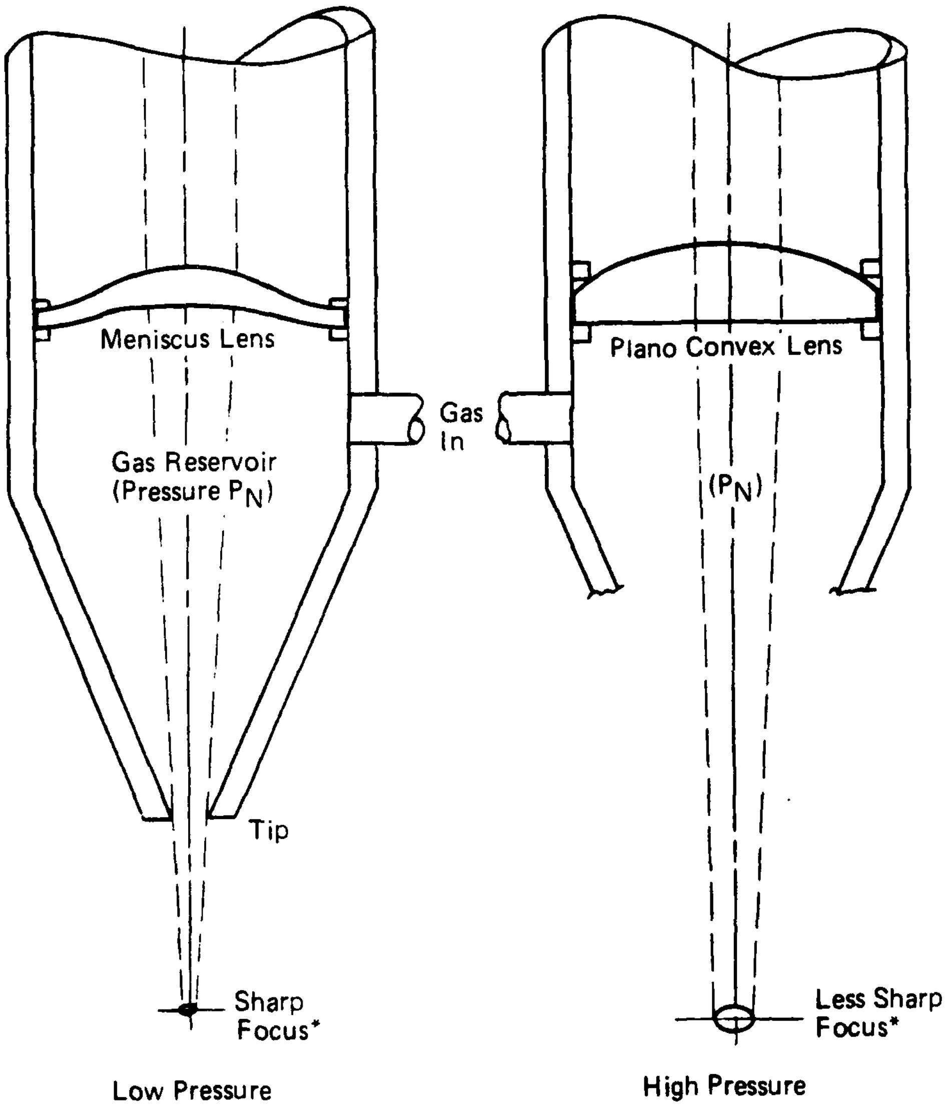
gap is increased from typical operating conditions (0.3-1.3 mm) to extreme conditions (10 mm). The direction of the subsonic stream is, however, influenced by small variations such as the damage or manufacturing tolerance outage. Thus the nozzle gap is kept small under practical cutting conditions to minimize stream/spot misalignment should directional changes occur.[20] Most cutting is accomplished at pressures where subsonic conditions exist.

4.4.2 Cutting with Supersonic Gas Flows

Higher pressures in the reservoir lead to a transition from uniform subsonic stream to the formation of a complex supersonic stream. Supersonic gas streams can contain regions where severe cutting pressure (P_C) variations occur over very short distances along the axis of flow. If the nozzle gap is extremely small, these discontinuities do not affect cutting performance and the advantages of higher pressure can be realized. However, as the gap approaches commercial practice, a severe drop occurs in cutting pressure (PC) and cutting performance. Switching to a nozzle with a noncircular or lobed throat cross section permits higher, more effective pressures to be used before discontinuities appear in the gas stream. Improvements in cutting speed of a 30% over conventional circular throat nozzle technology have been reported.[20] These improvements have been achieved with the work gap set at a commercially attractive 6.5 mm. The lobed throat cross section was in the form of a seven-pointed star. The use of lobed nozzles, however, does not eliminate the possibility of pressure discontinuities forming. Lobed nozzles delay the onset of discontinuities to higher pressures than circular nozzles. Even when discontinuities form, high pressure (Zone B)[20] regions can be found at certain points along the axis of flow (Figure 4-12). These points are at attractive distances from the nozzle for commercial cutting practices.

4.4.3 Higher Auxiliary Nozzle Pressure and Cutting Optics

The cutting lens forms one pressure barrier in the gas reservoir (Figure 4-13). The meniscus lens shown in the figure results in the sharpest focusing but may begin to distort as gas pressures increase. A planoconvex lens may have to be used for its greater resistance to deformation. However, the focusing sharpness of the planoconvex lens is less than that of the meniscus lens. The pressure at which the optical distortion caused by deflection of the meniscus lens has the same effect on the process as substitution of a planoconvex lens has been reported to be about 50-55 psig.[17]



RA8139RK

*Not to scale.

Figure 4-13. Cutting nozzle schematic.

REFERENCES

1. Llewellyn, S. A., "Factors that Determine the Specification of a CO_2 Laser Machining System," Proceedings of the Laser Processing Conference, Quebec City, Canada, 1986; published by Society of Photo-optical Instrumentation Engineers, Bellingham, Wash.

2. "1988 Buying Guide," published by Lasers and Optronics Magazine, Dover, N.J.

3. Znotins, T., "Industrial Application of Excimer Lasers," Proceedings of the Laser Processing Conference, Quebec City, Canada, 1986; published by Society of Photo-optical Instrumentation Engineers, Bellingham, Wash.

4. Luxon, J. T., Parker, D. E., and Plotkowski, P. D. <u>Lasers In Manufacturing</u>, Springer-Verlag, New York.

5. Levatter, J., "The Development of Industrial Excimer Lasers," Proceedings of the Laser Processing Conference, Quebec City, Canada, 1986; published by Society of Photo-optical Instrumentation Engineers, Bellingham, Wash.

6. Merchant, V. E., "Evolution of Carbon Dioxide Lasers for Materials Processing," Paper MS87-239 presented at the S-P-O-T '87 Conference; published by Society of Manufacturing Engineerings, Dearborn, Mich.

7. Sasnett, M. W., "Kilowatt-Class CO_2 Lasers Meet Present Industrial Needs," Laser Focus/Electro Opt. Mag., March 1988.

8. Wollerman-Windgasse, R., et al., "Multikilowatt Re-excited CO_2 Lasers and Their Application in Laser Materials Processing," Proceedings ICALEO '86, published by Laser Institute of America, Toledo, Ohio.

9. Hoffman, P. "The Start of a New Generation of CO_2 Lasers for Industry," Proceedings of 2nd International Conference on Lasers in Manufacturing, Birmingham, U.K., 1985, published by IFS Publications Ltd., Bedford, U.K.

10. Eckersley, J., "Ultra-Compact CO_2 Laser Ideal for Laserobots," Proceedings of Laser Robotics I, Ann Arbor, Mich., 1985, published by Society of Manufacturing Engineers, Dearborn, Mich.

11. Tauche, D., and Ruselowski, J., "Material Processing Systems for Manufacturing," <u>Proceedings of the Laser Processing Conference</u>, Quebec City, Canada, 1986; published by Society of Photo-optical Instrumentation Engineers, Bellingham, Wash.

12. Holmes, L., "Advances in Commercial Laser 1986-87," Laser Focus/Electro-Opt. Mag., Jan. 1987.

REFERENCES (contd.)

13. Anon., "Face-Pumped Lasers Enter Industry," Industrial Laser Review, Feb. 1988.

14. Small, T., "Laser Cutting at Work," Tool. Prod., Jan. 1988.

15. Private communication, Whitehouse Associates, Weston, Mass. (D. R. Whitehouse), March 1988.

16. Private communication, Coherent General (Shawn Murphy), March 1988.

17. Private communication, Leybold Vacuum Systems, Inc. (J. Capazzi), March 1988.

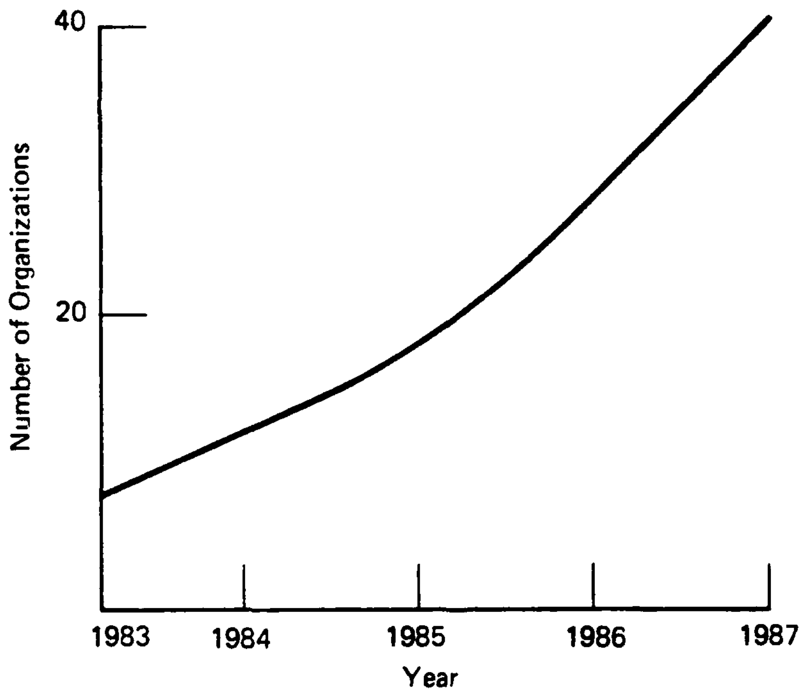
18. Anon., "Mirrors Focus Welding Beam From Industrial Lasers," Laser Focus/Electro-Opt. Mag., Nov. 1986.

19. Final Technical Report, "Laser Technology Application Survey," prepared by G.E. Aircraft Engines, Manufacturing and Quality Technology Organization for the U.S. Air Force, Ogden Air Logistics Center, Contract No. F42650-86-C-3384.

20. Fieret, J., et al., "Aerodynamic Interactions During Laser Cutting," Proceedings of Conference on Laser Processing Fundamentals, Vol. 668, Society of Photo-optical Instrumentation Engineers, Bellingham, Wash.

5. MANIPULATOR SYSTEMS

The state-of-the-art (SOA) relating to systems for manipulating the beam over the workpiece has progressed more rapidly than the process SOA and has kept pace with the laser SOA. Figure 5-1 shows the increase in the number of systems suppliers over the past several years. These are organizations that specialize in the design of the system and software while purchasing the control and laser from a specialist in those fields. As a result of this increase in systems specialization and emphasis, the early, specialized "flat goods" cutters have been supplemented by some more sophisticated beam manipulating schemes--many with three-dimensional capability. This increase in capability has resulted in a variety of manipulator options. These options



Source: Laser Buyers Guide 1983-1987

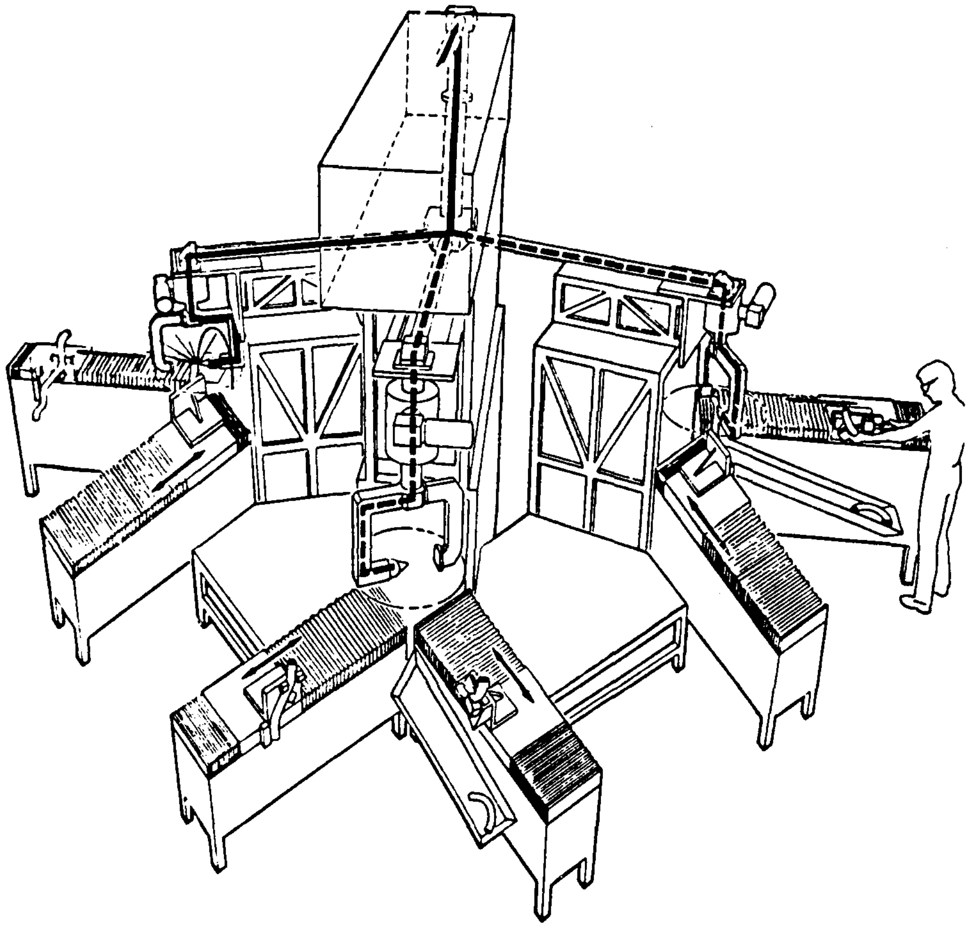
Figure 5-1. Growth of organizations that design and build systems only.

represent vast differences in cost and manipulative capability. The prospective user is faced with sorting out this array to select the most effective economic option. An overview and a classification of these options are needed to make sure that the prospective user is aware of the full scope of the SOA.

Laser manipulator systems can be divided, for purposes of this review, into two levels of complexity (and cost). Level 1 systems are based on a non-programmable manipulative pattern (e.g., cutting a circle through a simple rotation of the cutting nozzle). Level 2 systems are those that can perform a number of manipulative patterns, often accommodating the pattern to three-dimensional workpieces. Level 1 systems may cost only a fraction of the total laser cost. Level 2 systems often cost four times that of the laser. The Level 1/Level 2 characterization has been adopted in this review to make sure that the present emphasis on Level 2 systems in the literature does not obscure the existence of Level 1 systems such as that shown in Figure 5-2.

5.1 LEVEL 1 SYSTEMS: DEDICATED PATH MANIPULATORS

Figure 5-2 shows a Level 1 system that uses a simple rotational motion to cut stainless steel exhaust pipe. The Level 1 designation does not imply lack of sophistication.[1] For example, the system shown in Figure 5-2 shares the beam from a single laser among several work stations. However, the pattern of the cut is not programmable, hence the Level 1 designation. Typically, such a manipulative pattern could be adjusted for tube diameter and cut location. The tooling or optics might permit more than one cutting location obtainable through setup or by a simple tooling command from the system control. Motion in such systems can be applied by belts, cams, or hydraulic/air cylinders. In spite of their apparent simplicity of motion, Level 1 sytems may involve significant control considerations such as modulation of power during the cutting operation. A Level 1 system is often characterized by elaborate part-feeding systems because the limited action of the beam also suggests short process cycles with an accompanying need to move large numbers of parts through the process in order to justify the application. The system in Figure 5-2 uses shuttle tooling from three manual loading stations to move work from the shop environment to the enclosed beam. Vibratory, gravity, conveyor, or multi-station dial feed material handling systems might also be found on Level 1 equipment.



Source: Raycon Corp.

Figure 5-2. Typical Level 1 system for cutting exhaust pipe.

The Level 1/Level 2 concept also serves to relate cutting systems to a great deal of laser welding tooling where the limited-manipulation Level 1 concept has been applied to a number of high-volume, high-precision applications such as power train components.

5.2 LEVEL 2 SYSTEMS: PROGRAMMED PATH MANIPULATORS

Figure 5-3 illustrates a typical Level 2 system. This unit is a "flat stock" cutter with a moving beam designed for the cutting of surfaces represented by a single plane. This machine can carry out the cutting process in any pattern that can be traced on the surface of the work over the entire surface. The pattern is produced by numerical control and can be programmed off-line or by teaching in a typical Level 2 system. The ability to program the pattern of the cut differentiates a Level 2 from a Level 1 system.[1]

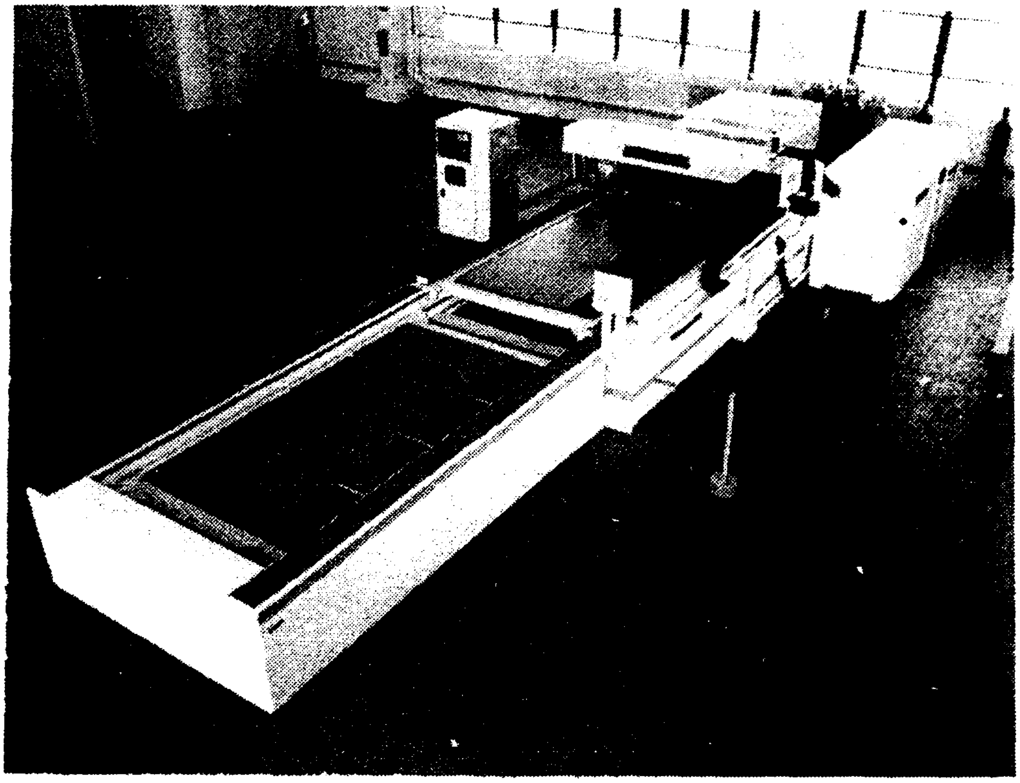
Most of the published work is about Level 2 systems. Industry sources worldwide agree on three types of Level 2 system:[2,3]

- Type 1: Beam stationary while workpiece moves.
- Type 2: Workpiece stationary while beam moves
- Type 3: Hybrid[4] or combined[3] systems where both optics and work move on programmable axes.

Each type has its advantages and disadvantages, and each type can be built in small or large sizes according to the workpiece. The length of the beam path often limits the size of the manipulator. Industry specialists recommend paths that do not exceed 5-6 m for practical maintenance of alignment.[5] One reference cites an upper limit of 10 m.[6] Very long beam paths often require special tailoring of the laser internal optics to minimize effects of beam divergence.[7]

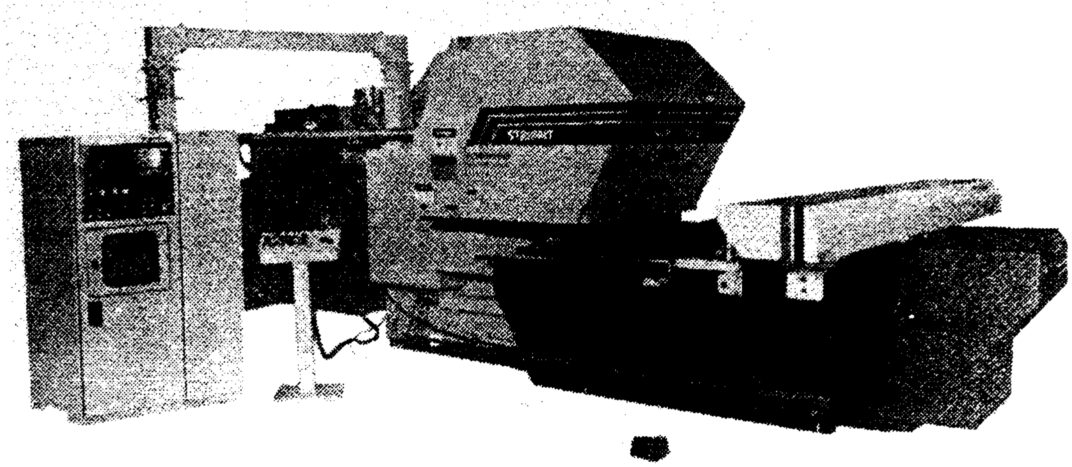
5.2.1 Level 2, Type 1 Systems (Beam Stationary/Work Moves)

For the most part, Level 2 Type 1 systems are for two-dimensional cutting. The beam path can be short with a minimum of mirrors. Because the work moves, Type 1 systems function best when the mass of all workpieces is similar. In 1978 a laser source combined with an NC turret punch was shown to the manufacturing community. These punch/laser combinations (Figure 5-4) have become the largest single subclass within the Type 1 category. Laser/punch



Source: Cincinnati, Inc.

Figure 5-3. Typical Level 2 system for programmed path cutting.



Source: Strippit-Houdaille, Inc.

Figure 5-4. Combination laser/punch configuration of Level 2, Type 1 system.

machines are used to fabricate flat sheet stock requiring the accuracy and quality of punched holes in conjunction with contour cutting capabilities to be utilized where nibbling or special tooling is impractical.[1]

Although Type 1 systems cut only in two dimensions, they must have some three-dimensional capability to accommodate changes in workpiece thickness and out-of-flatness in the material being cut. Out-of-flatness accommodation is achieved by adding a "Z" axis capability to the cutting head. The cutting head contains both the cutting nozzle and focusing lens. Two types of adaptive cutting heads are used to provide the Z-axis capability:

- Gravity heads that telescope up and down along the beam path guided by a hardened ring or roller configuration that rides on the work. This system is simple and not influenced by electrical conditions at the work surface. Gravity heads can only work on horizontal work surfaces.

- Proximity sensor heads that establish an electric field between a sensor that surrounds the nozzle and the work surface. Capacitive fields are most common for metal parts, where focus is critical. They are not influenced by the part except at edges. Mechanical probes connected to electro-mechanical transducers can be used. Optical sensors using the focusing and defocusing of diode lasers are also used.

5.2.2 Level 2, Type 2 Systems (Beam Moves/Work Stationary)

Large, complex, flimsy three-dimensional workpieces must often be fixed on stationary tooling to assure that they hold their shape during cutting operations. Thermal stresses and the imbalance of elastic forming stresses as material is removed can cause unacceptable part distortion during trimming and cutout operations on formed parts. The laser beam must be moved over such parts, which has led to the terms "flying spot" or "flying optics" for the Level 2, Type 2 manipulator.

The flying spot concept takes advantage of the improved system dynamics that can be achieved when all of the moving parts in the system are of constant mass. This advantage comes from restricting motion to manipulation of components of known mass such as drives, bridges, and optics. Variable mass workpieces therefore do not have to be moved. However, systems of this type must be designed for stability under oscillation over the entire working

envelope.* The work sits in a fixed position within the envelope of the flying optics (Figure 5-5).

<u>Beam Delivery</u>. The beam delivery system from the laser to the part is more complex for the Type 2 (flying optics) approach than for Type 1. Four beam delivery approaches have been considered:

(a) Laser mounted on the manipulator, or near the work
(b) Light pipes (waveguides or fiber optics)
(c) Independent articulated beam delivery optics
(d) Integral orthogonal beam delivery optics.

(a) <u>Laser on Manipulator</u> Mounting the laser on the manipulator axis directly at the work provides an ideal solution, and has been used in production for many years at power levels up to about 200 W. Advances in compact CO_2 lasers are now extending this, but there are still limitations. Nd:YAG lasers of the "slab" configuration are in test up to 600 W average power. Slab lasers could be mounted directly on the manipulator axis. Usually, however, some beam path elements such as mirrors are inserted between the laser and the cutting nozzle to provide the required directional flexibility.

(b) <u>Light Pipe</u> The light pipe approach is one method for optically connecting the laser to the cutting nozzle and is still under development. Fiber optics capable of carrying several hundred watts of Nd:YAG power have been developed and are in use (Figure 5-6). As noted in Section 4, CO_2 lasers will require development of a waveguide or the production of fiber optics in such infrared transmissive material as gallium arsenide. Neither of the CO_2 approaches is available on commercial metalworking equipment.

(c) <u>Independent Systems</u> Independent articulated beam delivery optics are assemblies of movable mirrors in tubes, Figure 5-7. One end is connected to the laser; the other end is attached to a manipulator. Such devices are being considered as a means for connecting lasers to commercially available industrial robots if such robots can provide suitable precision and stability.

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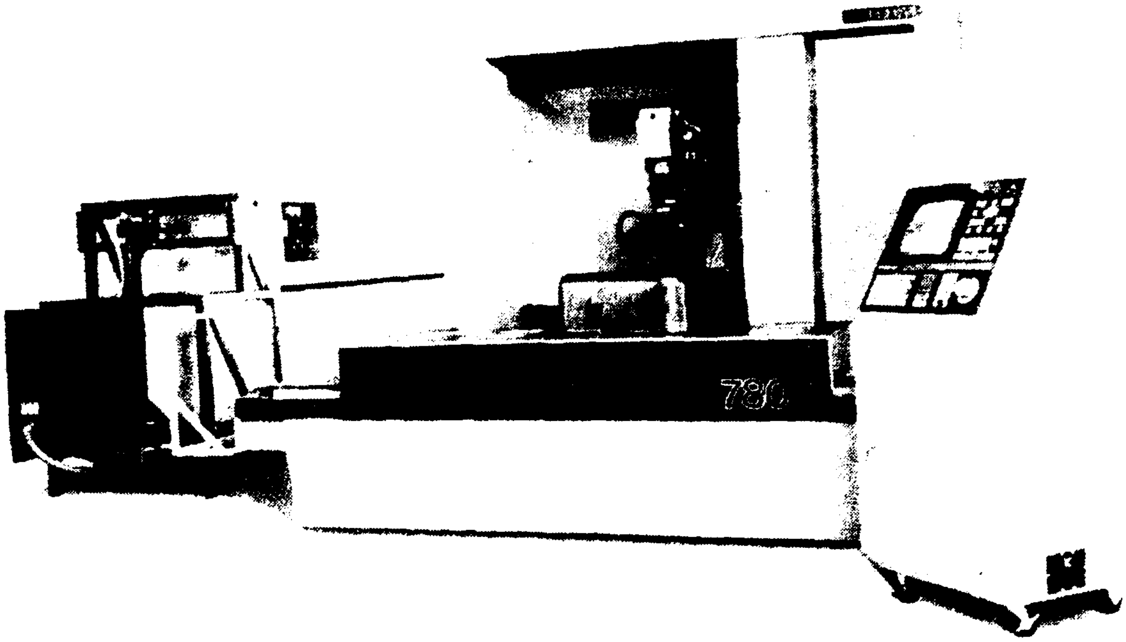
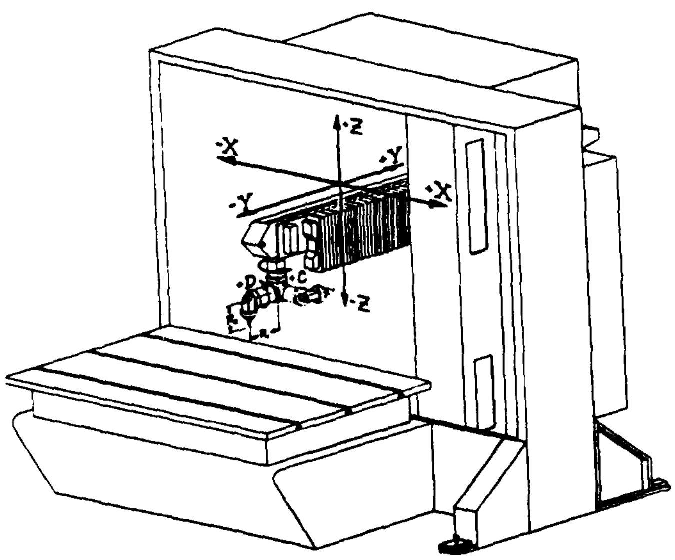
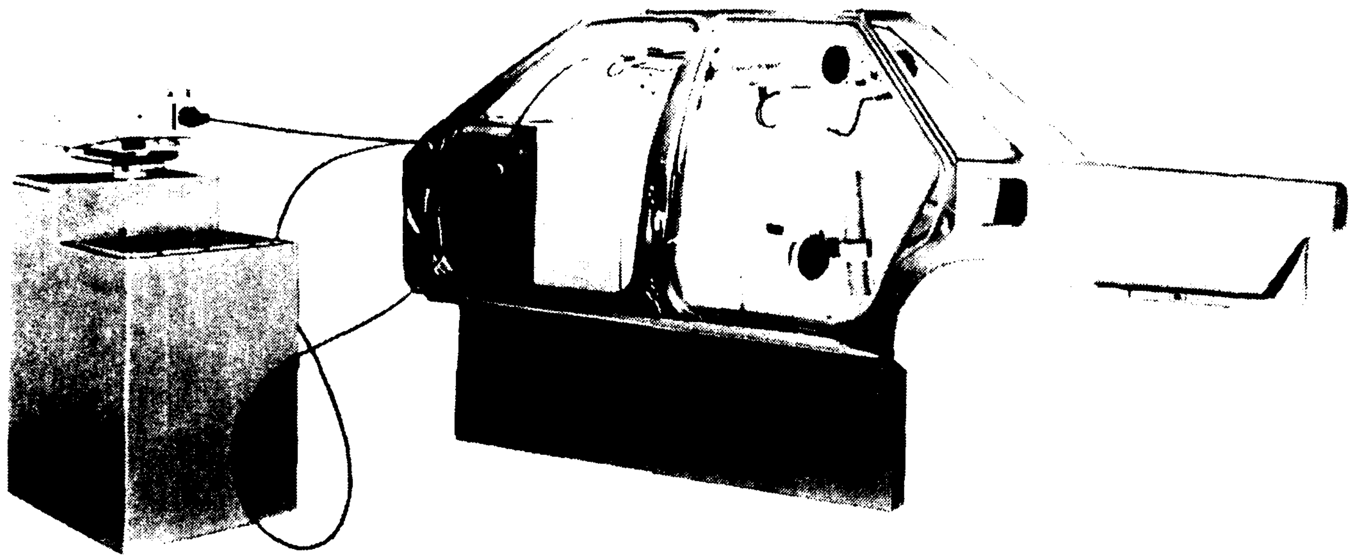
*Consideration must also be given to floor loadings, which may exceed standard factory specifications. Level 1, Type 2 systems should be placed on a monolithic slab.





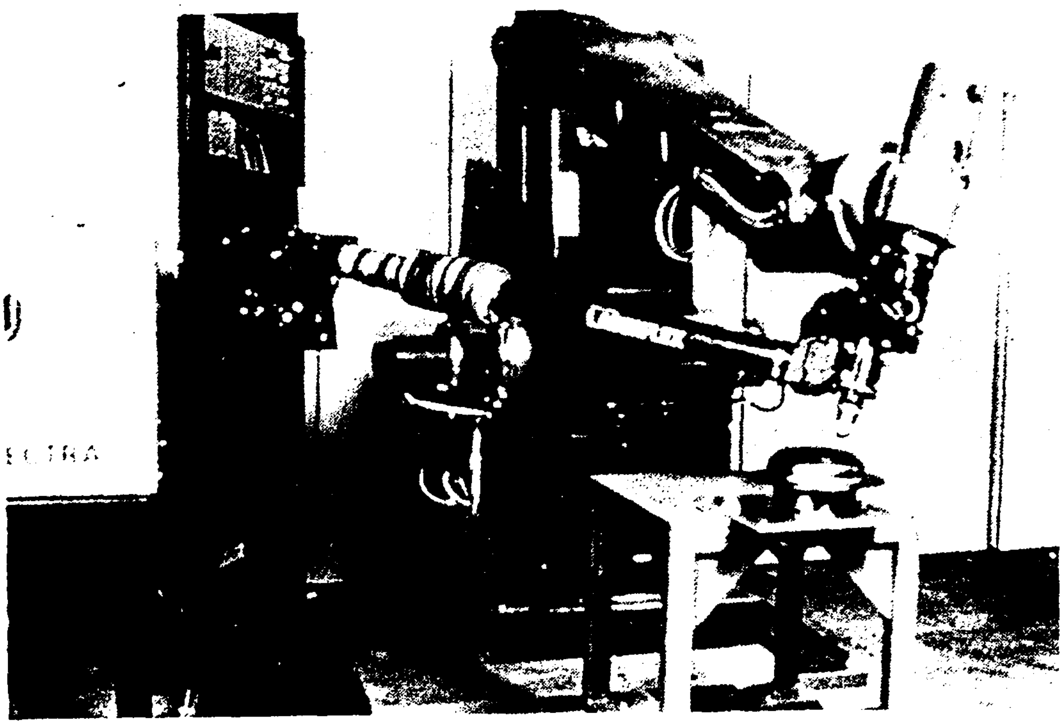
Source: Lumonics, Laserdyne Products

Figure 5-5. Level 2, Type 2 flying spot five-axis system with axis identification.



Source: Lumonics Material Processing Corp.

Figure 5-6. Fiber optic beam delivery system (limited to Nd:YAG lasers, 100 W max).



Source: Spectra-Physics, Inc.

Figure 5-7. Independent articulated, variable path length delivery system.

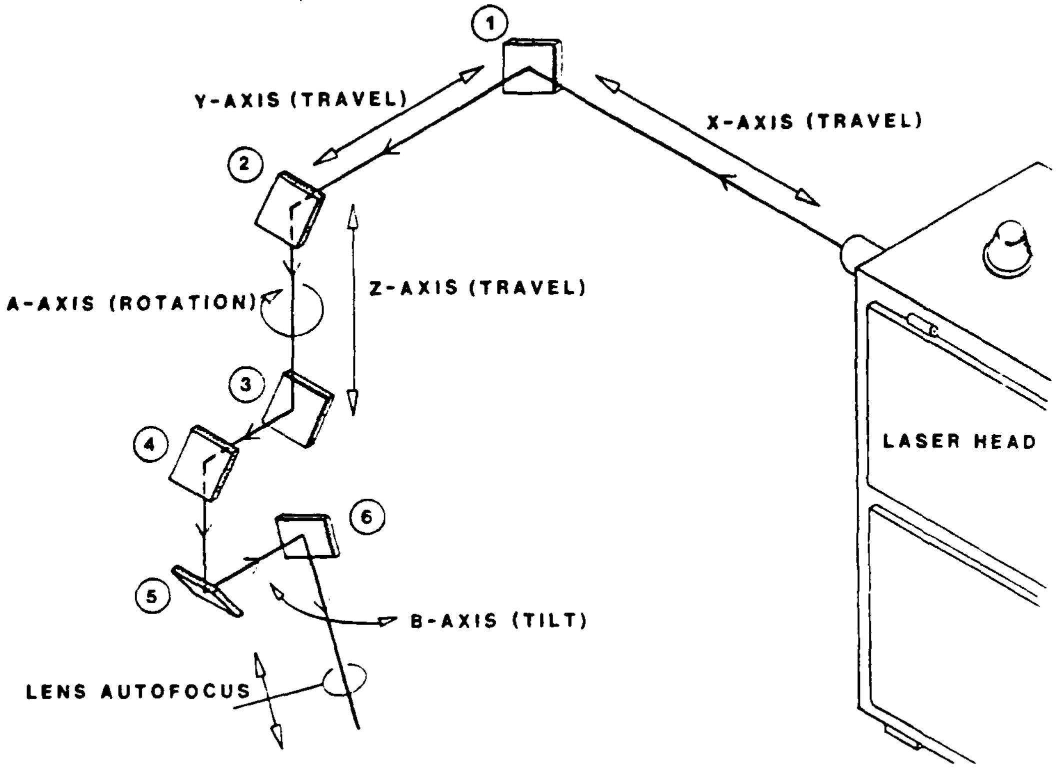
Independent articulated beam delivery systems may interfere with the motion of the manipulator or access to the work. Their principal use has been with welding robots.[6]

(d) Integral Systems. Integral orthogonal systems follow the paths of the motion axes with at least one deflection (turning) mirror per linear axis and two pairs of mirrors at optical shoulders where rotary axes are used. Thus a five-axis system may have as few as five or six mirrors because one mirror in each optical shoulder is also used as a deflection mirror (Figure 5-8). Mirrors cause a loss of power and require care in handling plus a certain amount of system engineering to maintain in alignment. Thus designers usually attempt to limit the number of mirrors. When the laser exhibits 45° linear polarization, one mirror in the system is a one-fourth wave phase shifter to provide circular polarization so that cuts will be uniform in all directions.

Most integral systems result in a variable-length path as the cutting head moves toward or away from the laser source. Beam diameter increases as distance from the laser increases. The focus characeristics of the lens depend on the diameter of the impinging beam. A large diameter gives the lens a low F number (i.e., small spot, short focal depth). If the lens moves to a portion of the beam with a smaller diameter, cutting capability may change. Expanding the beam diameter by means of added optics reduces the difference from point to point along the beam but does not eliminate it. Projecting a beam waist with a long Rayleigh range into the center of travel of the system greatly reduceds the spot size variation. Laser cavity optics sometimes must be tailored to project the waist an extra distance from the laser and well along the beam path of large manipulators.[7]

The mirror loss effect on power and the potential change in optical characteristics are the same for integral beam paths as they are for independent systems of the telescoping type.

Manipulator Options. The challenging applications that have been made feasible by the introduction of the moving beam concept have led to a number of configurations. Some of these configurations are discussed in this section.



Source: Leybold Vacuum Systems, Inc.

Note: (1) Two mirrors are often inserted between the laser and mirror 1 to simplify the task of bringing the beam into line with the first axis of motion without moving the laser itself.

(2) Mirrors 5 and 6 are eliminated in some systems where the system controller is capable of compensating for a final beam delivery point offset from the center line of the vertical (A) axis.

Figure 5-8. Integral, orthogonal beam delivery system (typical five-axis mirror arrangement with autofocus).

The flying optics concept can be applied to any number of axes up to five. Two axis moving beam systems are often used to cut thick nonmetallic plates; the third axis is used for thickness[9] adjustment. A Type 2 moving spot might be used to cut a part that could not be moved because it was already mounted on a pallet or conveyor. However, most moving beam applications represent the more challenging task of three-dimensional processing with three or five axes. Table 5-1 compares Type 1 against Type 2 systems and suggests when each would be the preferred choice.

Three- and five-axis Level 2, Type 2 manipulators are often called robots. Indeed, they meet the RIA* definition of an industrial robot as follows:

> "A reprogrammable multifunctional manipulator designed to move material, parts, tools or specialized devices through variable programmed motions for the performance of a variety of tasks."

Many laser manipulators are special-purpose robots, but general-purpose industrial robots have been applied as stand-alone manipulators or as two axes of a five-axis manipulator.[2] Industrial robots have also been considered as Level 2, Type 1 (fixed spot) devices to move the workpiece under the beam (Figure 5-9).

Manipulator Configurations. Two basic manipulator configurations have been reported in the literature:

- Cylindrical or polar coordinate articulated robots coupled through independent optical paths to the laser.[6,8]
- Cartesian coordinate gantry robots.[2,6,8]

The cylindrical or polar coordinate articulated robots have been used for welding[6] but do not seem to be as well suited for cutting as the gantry structure. One systems builder[6] cites declining strength of the arm as it is extended. With extension comes a proportional loss of positioning accuracy, profiling quality, and dynamics. This loss was considered to restrict the volume over which processing could be carried out. The circular working envelope of articulated robots was viewed as a further restriction. Table 5-2 lists pros and cons for the articulated robot.[8]

*Robot Institute of America.

TABLE 5-1. CONSIDERATIONS IN SELECTION OF LEVEL 2 CUTTING SYSTEMS

Comparison Criteria	Type 1 Work Moves, Beam Stationary	Type 2 Beam Moves, Work Stationary
Optical Requirements		
Constant focus all points in cutting range	+	-
Minimum Mirrors	+	-
Minimum Maintenance	+	-
Ease of Scrap Removal	+	-
Minimum Floor Space for Cutting		
X-Y Direction	-	+[a]
Symmetrical rotation[b]	0	0
Shape of Work		
Cut in single plane	+	0
Cut in several planes	-	+
Cut cylinders and disks[b]	0	0
Size/Weight of Work		
Light and constant	+	-
Heavy and constant	+	-
Very heavy or large and constant	-	+
Variable[c] (light and heavy)	-	+
Stability of Work		
Flimsy when moved	-	+
Needs tooling to minimize distortion	-	+[d]
Stable during cutting	+	0
Lowest Cost	+	-

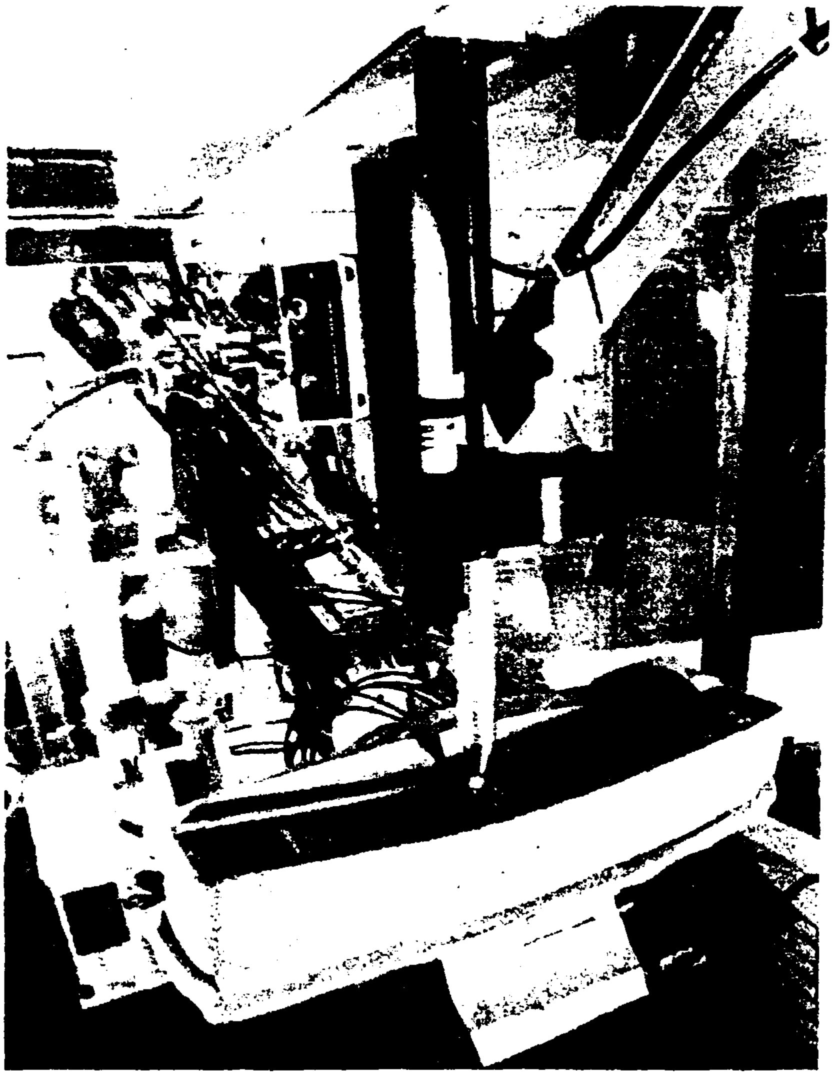
Legend: (+) should be considered.
(-) should be given less consideration.
(0) Not a consideration.

[a]Floor space ratio Type 1:Type 2 is typically 4:1 for a given workpiece size.[3]

[b]Parts that can be cut using symmetrical rotation are a special case in that the Type 1 system can be fitted with a stationary axis that is capable of either vertical or horizontal rotation and thus needs little floor space.

[c]Since the mass of the axis system is several times that of many parts, mass differences of the workpiece may not be significant, particularly when all pieces are relatively heavy and cutting speeds are low.[1]

[d]Only true if parts and/or tooling causes loads to vary with respect to mass.



Source: Ford Motor Co.

Figure 5-9. Robot moving work in Level 1, Type 1 application.

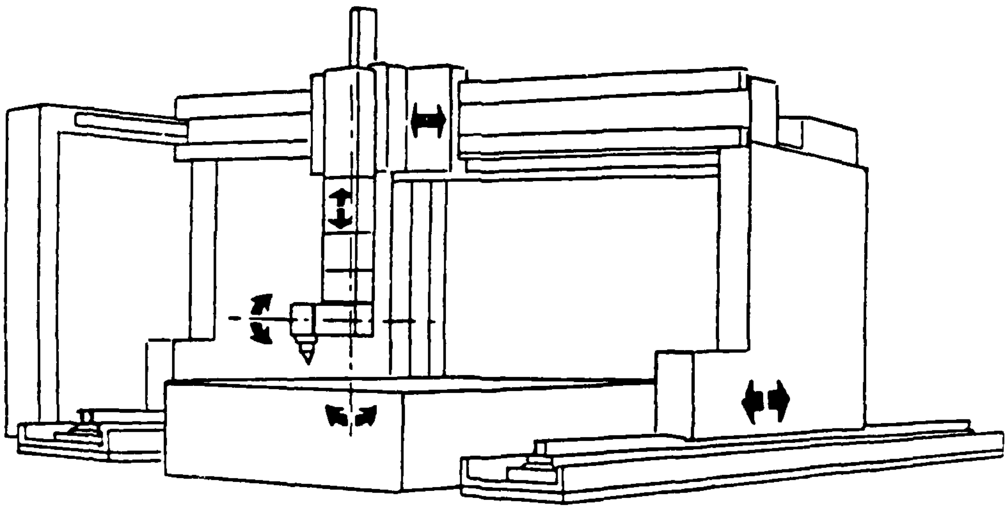
TABLE 5-2. PROS AND CONS: ARTICULATED ROBOT AS A BEAM MANIPULATOR[8]

Pro	Con
- Small floor space	- Lack of motion smoothness
- Convenient, easy to integrate to a variety of robots[a]	- Some limit of working volume
- Can reach into or under parts being processed	- More beam benders potentially, thus higher power losses
- Easy to program with TCP (tool center point)	- Insufficient accuracy and repeatability in many models
- Can work with large, heavy, or flimsy parts	- Possible interference of beam delivery system in work envelope (depends on setup)

[a]Many commercial robots come with well-developed off-line programming and CAD/CAM interface capability.

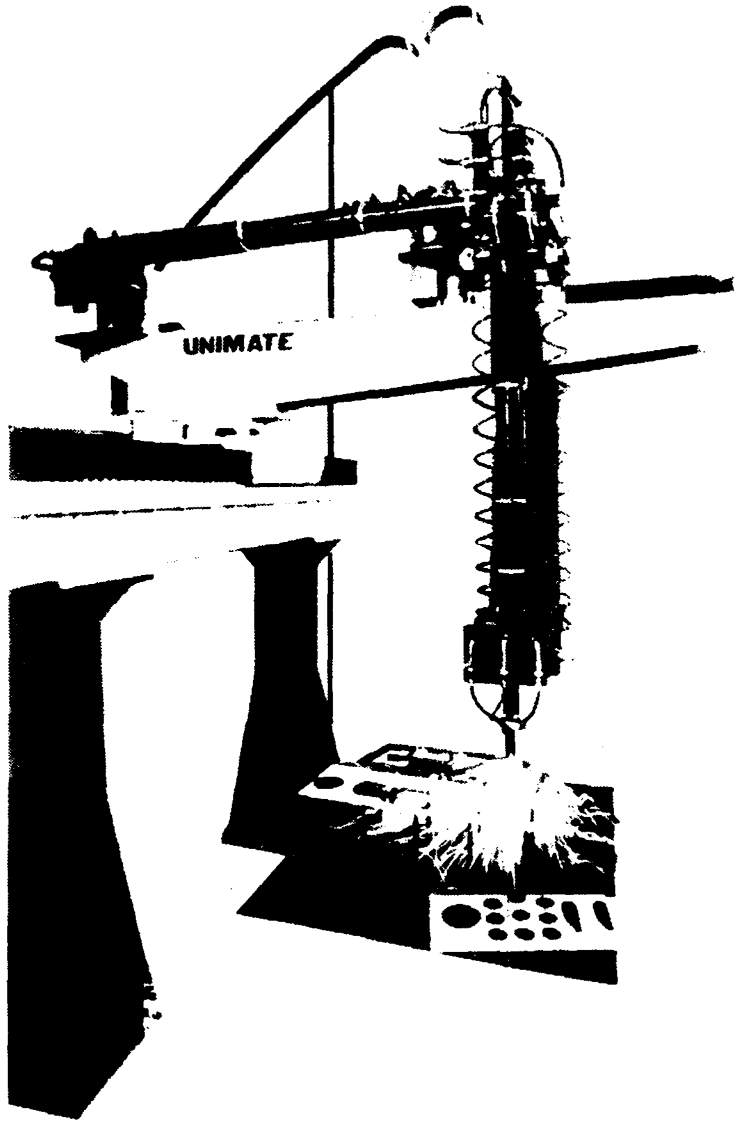
Cartesian coordinate gantry systems with integral beam delivery systems are used as the basis for most two- and three-dimensional cutting systems. Two configurations are used:

- Full gantry with both sides of the transverse axis supported (Figure 5-10)
- Open-sided gantry (Figure 5-11).



Source: Control Laser Corp.

Figure 5-10. Full gantry Level 2, Type 2 system.



Source: Westinghouse Electric Corp.

Figure 5-11. Open-sided gantry Level 2, Type 2 system.

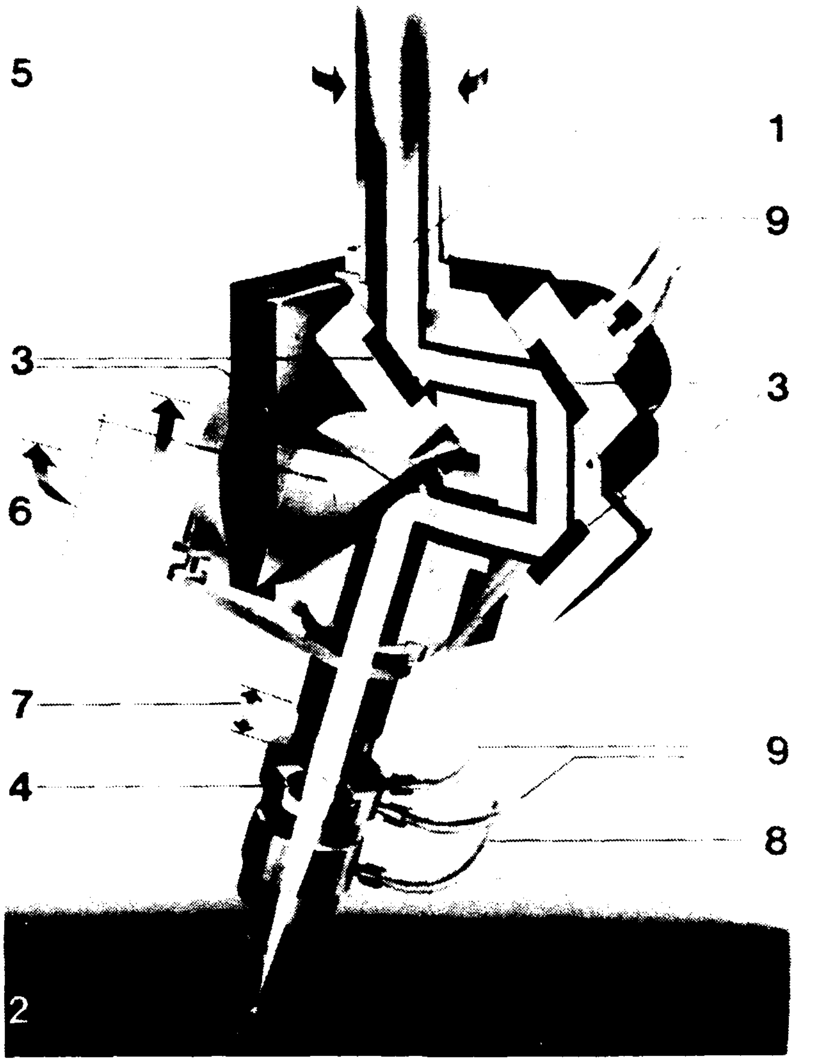
Full gantry systems are noted for their ability to be adjusted to very close working tolerances (±0.001 in. accuracy per foot of travel with ±0.002 in. repeatability).[6]

The open-sided (or cantilever arm) gantry provides improved work load/removal capability but involves an extended robot arm as one axis, a situation similar to that reported for articulated robots. However, accuracies of ±0.008 in. per axis and repeatability of ±0.005 in. are reported.[2] These values are closely related to the nominal tolerances of the mechanical system. Optical effects may add to these tolerances. Optical effects could result from alignment technique, pointing stability of the laser (typically under 0.15 mrad), and movement between laser and manipulater if they are mounted separately.

Table 5-3 lists pros and cons for the gantry approach.[8] The rotating/tilt head on gantry systems deserves some attention. The fourth and fifth axes on gantry systems are rotary (Figure 5-12). These rotating axes are often designated A and B (or C and D) to distinguish them from the conventional linear axes--specifically X, Y, and Z. The A and B axes may not be fully rotational and thus place some access limits on the system. The A-axis may be restricted to motion in a 180° to 200° sector. Other systems feature a full 360° motion. The tilt (or B) axis is usually restricted to ±90° from vertical. As a result of this restriction, the five-axis system cannot process the underneath surfaces. Some articulated robot/independent beam delivery systems are reported to be able to process underneath parts.[8] Gantry

TABLE 5-3. PROS AND CONS: GANTRY ROBOT AS A BEAM MANIPULATOR[8]

Pro	Con
- Large working volume	- Large footprint
- Smoother path on straight-line path (for some gantry robots)	- Not designed for working from under part
- Simple optics with standard beam benders (usually)	- Difficult to add extra two-axis motion
- Easy to program	- Requires up-front engineering to integrate a new robot



1 - Free Beam Path
2 - Work Surface
3 - Mirrors
4 - Focusing Lens
5 - A-Axis Rotation
6 - B-Axis Rotation
7 - Autofocus Motion
8 - Assist Gas
9 - Coolant Lines

Source: Rofin Sinar

Figure 5-12. Arrangement of mirrors to provide rotary fourth and fifth (A and B) axes on a 5-axis gantry system. (Maintains beam spot on center line of Z-axis of rotation.)

systems need a sixth axis in the form of a rotary table to turn the workpiece over for underside access. Such tables can often operate in the horizontal or vertical axis orientation.

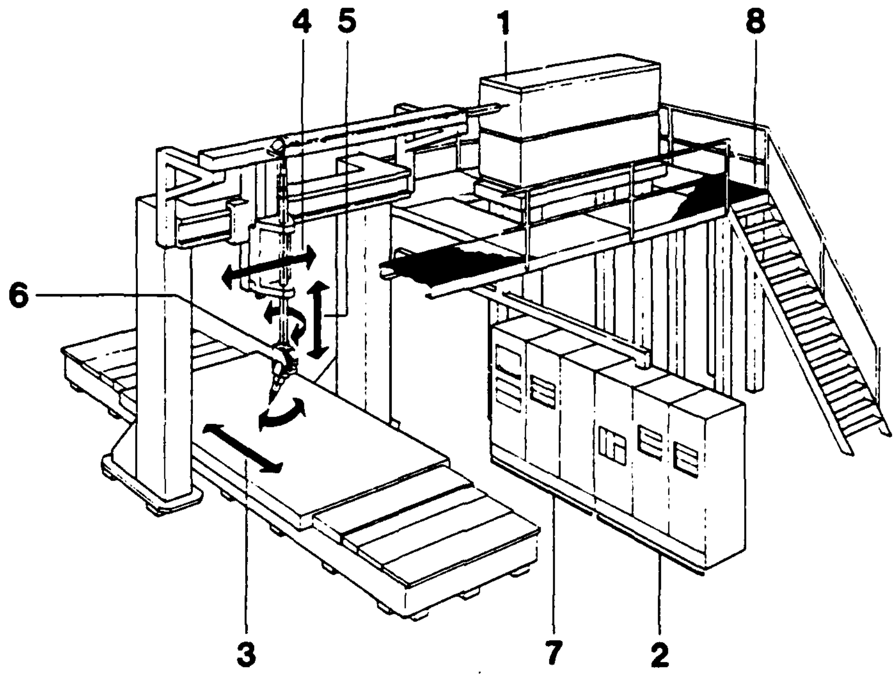
5.2.3 Level 2, Type 3 Systems (Hybrid or Combined)

The gantry systems can be modified so that the work moves on one axis and the spot travels on the others. Usually the long (X) axis is selected to carry the work (Figure 5-13). The beam delivery system need only accommodate the shorter Y, Z and (if present) A, B axes. The beam delivery path can be further shortened by mounting the laser so that its beam is introduced directly onto the stationary Y-axis.[9] Table 5-4 lists the pros and cons of the hybrid configuration.

5.3 SUMMARY

As the number of potential laser cutting applications has expanded, so has the number of manipulator options. The simplest manipulators follow a specific dedicated path configuration and emphasize rapid loading/unloading of parts. These Level 1 lasers offer reliability and accuracy where needed and at relatively low cost.

When the path must be changed from time to time, programmed path (Level 2) manipulators are available in many configurations. In the simplest (Type 1) the work moves and optics are stable. Type 1 lasers are usually applied to flat surfaces. For three-dimensional surfaces the beam must move with greater freedom. Flying spot systems are usually incorporated into some type of robots. Consideration has been given to the use of commercial articulated robots, but the most accurate Type 2 systems are built onto gantry robots. Flying spot systems work well with flimsy parts or parts that must be fastened down to maintain shape.



1 - Laser Source
2 - Controls
3 - X-Axis
4 - Y-Axis
5 - A-Axis Rotation
6 - B-Axis Rotation
7 - Controls
8 - Service Platform

Source: Leybold Vacuum Systems, Inc.

Figure 5-13. Hybrid gantry Level 2, Type 3 system.

TABLE 5-4. PROS AND CONS: HYBRID CONFIGURATION OF GANTRY[a] BEAM MANIPULATOR

Pro	Con
- Shorter beam path with Y-axis fixed[3] - Moving axis delivers[4] part outside of gantry--quick, low-cost unload/load - Load/unload permits complex[4] palleting to proceed while loaded part is being machined.	- Limited mass on moving axis - Reduced accuracy and repeatability if mass of work varies greatly from application to application

[a]From Reference 8 with additions as noted.

REFERENCES

1. Private communication, Lumonics Material Processing Corp. (R. Gustafson), March 1988.

2. Soroka, D. P., and Swensrud, R. L., "Application of the Westinghouse Laser System," Paper M587-237, Proceedings of S-P-O-T '87 Conference, Society of Manufacturing Engineers, Dearborn, Mich.

3. Honma, S., "Laser Cutting Technology Growing Further," Metalwork. Eng. Mark., July 1987.

4. Anthony, P., Capazzi, J., and Powers, D., "Multi-Dimensional Laser Processing System," Proceedings of the Laser Processing Conference, Quebec City, Canada, 1986, published by Society of Photo-optical Instrumentation Engineers, Bellingham, Wash.

5. Private communication, Leybold Vacuum Systems (J. Capazzi), March 1988.

6. Held, J., "TRANSLAS-A 5-Axis Gantry Laser System," Proceedings of Laser-Robots II, sponsored by Society of Manufacturing Engineers (SME), Dearborn, Mich., March 1987.

7. Private communication, Spectra-Physics, Inc. (T. Webber), March 1988.

8. Tight, T., "Review of Laser-Robotics-Challenges Remaining to Fully Develop the Technology", Proceedings ICALEO '85, published by Laser Institute of America, Toledo, Ohio.

9. Mizutame, M., "Some Considerations of Laser Machining Systems Used in Electric Company," Proceedings ICALEO '85, published by Laser Institute of America, Toledo, Ohio.

6. CONCLUSIONS

This review has documented the state-of-the-art in terms of cutting quality, rates, limits, and available equipment. This documentation also suggests several conclusions about the future as follows:

(1) There should be a continuing emphasis on pulsed CO_2 technology. Pulsing has only become available on multikilowatt CO_2 lasers within the last few years. CO_2 lasers have the ability to switch from CW to pulsed power. The ability to switch power delivery modes becomes increasingly important as manipulators become capable of following more complex paths involving increasingly finer detail.

(2) CO_2 lasers pulse at higher rates than Nd:YAG and consequently cut more rapidly.

(3) Even though CO_2 pulses typically have lower peak power, they have sufficient power to break down reflectivity and are used to cut highly reflective metals such as aluminum.

(4) CO_2 pulse frequency is controllable and can be adjusted to reduce cut face roughness.

(5) CO_2 pulse technology offers several optional modes not otherwise available. An example would be dross-free cutting of aluminum using hyper pulse wherein a substantial CW power level can be maintained while spikes of power are added to break down reflectivity.

(6) Interest in Nd:YAG technology as a beam source for the cutting of metals and nonmetals will continue as a result of trends that are currently identifiable.

(7) Nd:YAG power has been increasing until it now challenges CO_2 technology at the kilowatt level. Emerging slab laser technology opens the possibility for improving Nd:YAG beam quality.

(8) Nd:YAG may become the choice for cutting some composite materials where the combined materials are not effectively cut by the CO_2 technology. The CO_2 beam will continue to dominate the cutting of organic materials such as plastics and organic/organic composites because its wavelength is efficiently absorbed. However, even

this advantage may be challenged by an emerging technology involving the excimer family of lasers. The excimer beam is being evaluated to determine if it cuts using a nonthermal interaction with chemical bonds in organic materials.

(9) Nd:YAG is a compact beam source, and the beam is amenable to transmission with fiber optics. Both of these characteristics may be of interest in future manipulator designs.

(10) Fiber optic beam transmission technology appears to have reached a point in its development where several hundred watts of average power can be transmitted. The more complex fibers that will be required to carry CO_2 laser beams are under development, but do not yet transmit usable cutting power levels.

(11) Manipulator design will continue to evolve at the two levels identified in this review. However, the availability of compact lightweight lasers with beam power approaching kilowatt level plus fiber optic systems will permit less cumbersome optical systems in future flying spot systems. Gantry/orthogonal manipulators will prevail. Extensive linkage of commercial articulated work-handling robots to lasers will be hindered by present limitations in path accuracy and work envelope.

(12) Process technology improvements will relate to surface finish and kerf widths to prevent these quality elements from limiting the ability of improved manipulator to produce increasingly finer detail on laser-cut parts. Cutting speeds currently outrun manipulator speeds.

(13) Improvements in process rates and quality will be supported by increased use of supersonic flow rates for cutting gases. Inconsistencies encountered by some earlier supersonic applications have been reduced through the use of gas nozzles with noncircular throats.

BIBLIOGRAPHY

The following papers represent a selected list of current publications that discuss equipment and processes for laser cutting. For the most part, these publications provide a concise overview of the topic and avoid theoretical discussions.

Anon., "Water-Jet and Laser Cutters Take on Tough Materials," Plastics Technology, **33** (1), January 1987, pp. 13,15,17.

Anon., "Some Findings in Cutting Composites," Am. Mach. Autom. Manuf., **130** (8), August 1986, p. 29.

Anon., Machining Data Handbook, Vols.1 and 2, 3rd Ed., Machinability Data Center, Metcut Research Associates, Cincinnati, Ohio, 1980.

Anon., "Machinine Metals at Ultrahigh Speeds," Mater. Eng., **94** (2), August 1981, pp. 44-47.

Anon., "Cutting and Edge Preparation for Welding," Weld. Rev., **1** (1), February 1982, pp. 26, 29-30, 33-34.

Anon., "Profile Cutting of Stainless Steel Using Plasma and Laser Techniques," Stainless Steel Ind., **14** (80), July 1986, pp. 15, 17.

Anon., "Laser Versus Mechanical Cutting Methods," Sheet Met. Ind., **62** (11), November 1985, p. 588.

Arata, Y., Maruo, H., Miyamoto, I., and Takeuchi, S., "Dynamic Behavior in Laser Gas Cutting of Mild Steel," Trans. Jap. Weld. Res. Inst., **8** (2), 1979, pp. 175-186 (in English).

Balbi, M., and Silva, G., "Stainless Steel Plate Cutting: Thermal and Mechanical Cutting, III. Laser Cutting - Some Observations," Avesta Stainless Bull., **6** (4), October-December 1982, pp. 3-11.

Berardi, E., "Robot, Laser Tridimensional Cutting Technology Detailed," JPRS-WST-85-020, July 1985, pp. 14-20; available from NTIS (N85-31333). Translated into English from ATA-Ingr. Automobilistica (Turin), Dec. 1984, pp. 815-822.

BNF Metals Technology Centre, "Copper Cutting--by Laser," SAMPE J., **23** (4), July-August 1987, p. 83.

Bohme, D., "Thermal Cutting with Optimized Cutting Plans," FWP J., **20** (6), June 1980, pp. 73-74, 76, 78, 80, 82, 84, 86-87.

Crane, K.C.A., and Brown, J. R., "Laser-Induced Ablation of Fibre/Epoxy Composites," J. Phys. D: Appl. Phys., **14**, December 14, 1981, pp. 2341-2349.

Darchuk, J. M., and Migliore, L. R., "Guidelines for Laser Cutting," Lasers Appl., **4** (9), September 1985, pp. 91-97.

Field, R., "The Laser--an Alternative to the Punch Press," Hydraul. Pneum. Mech. Power, **28** (328), April 1982, pp. 134-135.

Fieret, J., and Ward, B. A., "Circular and Non-Circular Nozzle Exits for Supersonic Gas Jet Assist in CO_2 Laser Cutting," 3rd International Conference on Lasers in Manufacturing, Paris, France, 3-5 June 1986; IFS Publications, Ltd., Bedford, U.K., 1986, pp. 45-54.

Forbes, N., "Die Board Cutting by CO_2 Laser," Proceedings of the Society of Photo-Optical Instrumentation Engineers, **247**, Adv. in Laser Eng. and Appl., San Diego, Calif., July 31-August 1, 1980, pp. 8-17.

General Motors Institute, "Ventilate When Cutting Kevlar," Am. Mach. Autom. Manuf., **131** (1), January 1987, p. 27.

Gettleman, K., "Cutting Stamping Dies with a Laser," Mod. Mach. Shop, **56** (8), January 1984, pp. 50-58.

Habercom, G. E., Jr. (Ed.), Laser Cutting and Machining: Nonmetals (Citations from the Engineering Index Data Base), Search Period 1970-July 1979, NTIS, Springfield, Va., PS-79/0891/-EES, September 1979, 130 pp.

Hodge, D., "Stainless Steel Profiling: A Review," Sheet Metal Ind., **57** (1), January 1980, pp. 37-40, 69.

Honma, S., "Laser Cutting Technology Growing Further," Metalwork. Eng. Mark., **9** (4), July 1987, pp. 64-69.

Janjua, M. S., "Micro Controls Laser in Sheet Metal Cutting," Sheet Met. Ind., **61** (10), October 1984, pp. 558, 561, 562, 564.

Johnson, T., "FLMS Systems - A New Generation of Machine Tool?" Prod. Eng. (London), **62** (12), December 1983, pp. 16-17.

Kamula, J. N., and Steen, W. M., "The Importance of Gas Flow Parameters in Laser Cutting," in: Lasers in Metallurgy, Chicago, Ill., February 22-26, 1981, pp. 263-278; published by Met. Soc. AIME, Warrendale, Pa., 1981.

Karow, J., "Shape Cutting Steel: Comparing Three Methods," Fabricator, **14** (5), July-August 1985, pp. 34-35.

Kechemair, D., Zavidovique, B., Foulloy, L., and Gerbet, D., "A Laser Metal Cutting Robot with a Rule Based 'Heart'," in: The Laser vs. the Electron Beam in Welding, Cutting and Surface Treatment: State of the Art, Vol. 1, Conference at Reno, Nev., November 6-8, 1985; published by Bakish Materials Corp., Englewood, N.J., 1985, pp. 182-194.

Kokosa, J. M., and Doyle, D. J., "By-Products Produced During CO_2 Laser Cutting of Glass Reinforced Polyester," in: Polymeric Materials Science and Engineering, Symposia held at the 192nd National Meeting of the American Chemical Society, Anaheim, Calif., September 7-12, 1986; Proceedings of ACS Division of Polymeric Materials: Science and Engineering, **55**, 1986, p. 904.

Kollmansberger, R. B., and Botkin, M. N., "F-15 Composite Speedbrake in Production," in: Bicentennial of Materials, Proceedings of the Eighth National Technical Conference, Society for the Advancement of Material and Process Engineering, Seattle, Washington, October 12-14, 1976, pp. 138-154.

Kuneida, M., and Nakagawa, T., "Development of Laminated Drawing Dies by Laser Cutting," Bull. Jap. Soc. Precis. Eng., **18** (4), December 1984, pp. 353-354 (in English).

Lee, C. S., Goel, A., and Osada, H., "Parametric Studies of Pulsed-Laser Cutting of Thin Metal Plates," ICALEO '84, Vol. 44--Materials Processing, Boston, Mass., November 12-15, 1984; published by Laser Institute of America, Toledo, Ohio, pp. 86-93.

Lepore, M., and Esposito, C., "On the Maximum Limit Value in the Cutting Speed with a Plane Polarized Laser Beam," Appl. Phys. Commun., **4** (2-3), 1984, pp. 121-134.

Lilja, I., "Laser Cutting - FMS Cell with a Future," Proceedings of the 4th International Conference on Flexible Manufacturing Systems, Stockholm, Sweden, October 15-17, 1985; published by IFS Publications, Ltd., Bedford, U.K., 1985, pp. 147-156.

Llewellyn, S. A., "Laser Cutting--State of the Art," in: The Laser vs. the Electron Beam in Welding, Cutting and Surface Treatment, State of the Art, Vol. 1, Conference at Reno, Nev., November 6-8, 1985; published by Bakish Materials Corp., Englewood, N.J., 1985, pp. 171-181.

Lunn, D. J., "Process Alternatives: Nibbling, Laser Cutting and Plasma-Arc Cutting," Tool. Prod., **46** (12), March 1981, pp. 66-69.

Martyr, D. R., "Cutting and Welding Stainless Steel Using High Power CO_2 Lasers," Stainless Steel Ind., **13** (76), November 8, 1985.

Mello, M. D., "Laser Cutting of Non-Metallic Composites," in: Laser Processing: Fundamentals, Applications, and Systems Engineering, Proceedings of Conference, Quebec City, Canada, June 3-6, 1986; Proc. SPIE, **668**, 1986, pp. 288-290.

Miner, L. H., "Cutting and Machining Kevlar Aramid Composites," in: Kevlar Composites, Proceedings of the Symposium, El Segundo, Calif., December 2, 1980; El Segundo, Calif., Technology Conferences, 1980, pp. 85-93.

Moriyasu, M., Hiramoro, S., Hoshinouchi, S., and Ohmine, M., "Adaptive Control for High-Speed and High Quality Laser Cutting," in: Laser Welding, Machining and Materials Processing, Conference at San Francisco, Calif., November 11-14, 1985; published by IFS Publications Ltd., Bedford, U.K., 1986, pp. 129-136.

Mosavi, R. K., "Comparing Laser and Waterjet Cutting," Laser Optronics, **6** (7), July 1987, pp. 65-68.

Nielsen, S. E., "Laser Cutting with High Pressure Cutting Gases and Mixed Gases," 3rd International Conference on Lasers in Manufacturing, Paris, France, June 3-5, 1986; published by IFS Publications, Ltd., Bedford, U.K., 1986, pp. 25-44.

Nilsson, K., and Sarady, I., "Cutting and Welding Three-Dimensional Sheet Metal Parts with High Accuracy," in: Lasers in Manufacturing, First International Conference, Brighton, U.K., November 1-3, 1983; published by IFS Publications, Ltd., Bedford, U.K., 1983, pp. 79-86.

Postier, R. A., "Factory Automation for Composite Structures Manufacturing," SAMPE Quarterly, **16**, April 1985, pp. 45-49.

Powell, J., and Menzies, I. A., "Principles and Applications of Carbon Dioxide Laser Cutting," Proceedings of the Second Conference on Materials Engineering, London, U.K., November 5-7, 1985; Mechaical Engineering Publications, Suffolk, U.K., 1985, pp. 205-213.

Rosecrans, L. B., "Effects of Laser-Cutting Selected Properties of Inconel 718," Digest of Technical Papers, Conference on Lasers and Electro-Optics, Anaheim, Calif., June 19-22, 1984; published by IEEE, New York, 1984, pp. 146-148.

Saunders, R. J., "Laser Metalworking," Met. Prog., **126** (2), July 1984, pp. 45, 47-48, 50-51.

Salyer, R. A., "Applications for Industrial Lasercutter Systems," in: Industrial Applications of High Power Laser Technology, Proceedings of the Seminar, San Diego, Calif., August 24-25, 1976, pp. 50-59; published by SPIE, 1976, pp. 50-59.

Schaffer, G., "Laser Cutting Replaces Blanking," Amer. Mach., **122** (12), December 1978, pp. 100-103.

Schier, J. F., and Juergens, R. J., "Impact of Composites on Fighter Aircraft. II - Composites New Look to the Aircraft Production Line," Astronautics and Aeronautics, **21**, October 1983, pp. 41-45.

Sepold, G., and Rothe, R., "Laser Beam Cutting of Thick Steel," ICALEO '83, Vol. 38--Materials Processing, Los Angeles, Calif., November 14-17, 1983; published by Laser Institute of America, Toledo, Ohio, 1984, pp. 156-159.

Sepold, G., Teske, K., and Rothe, R., "Investigations on Laser Melt Cutting of Metals," Colloquium on Thermal Cutting and Flame Processes, Ljublijana, Yugoslavia, September 7, 1982; published by International Institute of Welding, London, U.K., 1982.

Steen, W. M., "The Laser: An Industrial Tool," Met. Soc. World, 1 (7/8), July-August 1982, pp. 12-13.

Tagliaferri, V., and Crivelli-Visconti, I., "Cutting of Aramidic Fibre Composites with CO_2 CW Laser," in: Developments in the Science and Technology of Composite Materials, Proceedings of the First European Conference on Composite Materials and Exhibition, Bordeaux, France, September 24-27, 1985, pp. 687-693 (in English); published by Association Europeenne des Materiaux Composites, Bordeaux, France, 1985, pp. 687-693.

Tagliaferri, V., Di Ilio, A., and Crivelli-Visconti, I., "Laser Cutting of Fibre-Reinforced Polyesters," Composites, **16** (4), October 1985, pp. 317-325.

Tal, Y., Lenz, E. and Shachrai, A., "Temperature Controlled Laser Cutting," ICALEO '82, Vol. 31--Materials Processing, Boston, Mass., September 20-23, 1982; published by Laser Institute of America, Toledo, Ohio, pp. 149-161.

Tamaschke, W., "Behrens 5 Axis Laser Cutting System," Tech. Pap. Soc. Manuf. Eng., Paper MS85-496, 1985, 12 pp.

Thomassen, F. B., and Olsen, F. O., "Experimental Studies in Nozzle Design for Laser Cutting," in: Lasers in Manufacturing, First International Conference, Brighton, U.K., November 1-3, 1983; published by IFS Publications, Ltd., Bedford, U.K., 1983, pp. 169-180.

Vaccari, J. A., "The Laser's Edge in Metalworking," Am. Mach., **128** (8), August 1984, pp. 99-110, 112-114.

Vancleave, R. A., "Laser Cutting Shapes in Plastics," Bendix Report BDX-613-2727, DE82-007647; avail. NTIS (82-29594), December 1981, 49 pp.

Vancleave, R. A., "Characteristics of Laser Cutting Kevlar Laminates," Bendix Report BDX-613-2075-Rev, avail. NTIS (N80-11456), January 1979, 28 pp.

Vancleave, R. A., "Laser Cutting Plastic Materials," Bendix Report BDX-613-2476, avail. NTIS (N81-12417), August 1980, 42 pp.

Vancleave, R. A., "Laser Cutting Plastics," Bendix Report BDX-613-2906, DE83-011130, avail. NTIS (N83-33145), April 1983, 20 pp.

Vicanek, M., Simon, G., Urbassek, H. M., and Decker, I., "Hydrodynamical Instability of Melt Flow in Laser Cutting," J. Phys. D: Appl. Phys., 20 (1), January 14, 1987, pp. 140-145.

Weick, J. M., "Laser Cutting of Steel Panels in Two and Three Dimensions," Ind. Prod. Eng., 10 (3), 1986, pp. 115-117.

Weskott, D., Scheuerman, W., and Herbrich, H., "Refinements Boost Laser's Cutting Attractions," Weld. Met. Fabr., 51 (3), April 1983, pp. 149-150.

Wilhelmy, H., "NC Applied to Flame, Plasma and Laser Cutting," in: Computer Aided Engineering--Today's Technology, Annual Technical Conference - Numerical Engineering Society, London, England, April 20-21, 1983, 15 pp.

Winship, J. T., "CNC Lasers Cut Out Saw Blades," Amer. Mach., 128 (5), May 1984, pp. 92-94.

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